PB84-118249

Handbook for Evaluating Remodial Action Technology Plans

Little (Arthur D.), Inc., Cambridge, MA

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Aug 83

U.S. Department of Commerce
National Technical Information Service
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1. REPORT NO. EPA-600/2-83-076	2.	3. RECIPIENT'S ACCESSION NO. PB84 118249
4. TITLE AND SUBTITLE HANDBOOK FOR EVALUATING REMEDIAL ACTION TECHNOLOGY PLANS		5. REPORT DATE August 1983 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) John Ehrenfeld and Jeffrey Bass		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Arthur D. Little, Inc. Acorn Park Cambridge, Massachusetts 02140		10. PROGRAM ELEMENT NO. TEJY1A 11. CONTRACT/GRANT NO. 68-01-5949
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory--Cin.,OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Final; Oct. 1981 to June 1982 14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES

Project Officer: Herbert R. Pahren, 513/684-7871

16. ABSTRACT

This report contains information on over 50 remedial action technologies. A brief description, status, factors for determining feasibility and reliability, principal data requirements, and basic information for cost review are given for each technology. In addition, a general discussion of the major pathways and associated remedial approaches and of monitoring techniques have been included.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 459
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

United States
Environmental Protection
Agency

Municipal Environmental Research
Laboratory
Cincinnati OH 45268

EPA-600/2-83-076
August 1983

PB84-118249

Research and Development

EPA

Handbook for Evaluating Remedial Action Technology Plans

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

EPA-600/2-83-076
August 1983

HANDBOOK FOR EVALUATING REMEDIAL ACTION TECHNOLOGY PLANS

by
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EPA Contract 68-01-5949

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MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
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DISCLAIMER

The information in this document has been funded wholly or in part by the United States Environmental Protection Agency under Contract 68-01-5949 to Arthur D. Little, Inc. It has been subject to the Agency's peer and administrative review and has been approved for publication. The contents reflect the views and policies of the Agency. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

This manual is intended to present information on technologies that may be applicable to specific problems of controlling hazardous wastes at disposal sites. It is not intended to cover any technology exhaustively, nor is the subject of alternative disposal methods addressed except in the context of remedial measures at uncontrolled sites. Neither are the topics of quick- or short-term remedial response actions or management/ manifesting procedures considered to be appropriate for inclusion in this manual.

FOREWORD

The Environmental Protection Agency was created because of increasing public and governmental concern about the nation's environment and its effect on the health and welfare of the American people. The complexity of the environment and the interplay among its components require a concentrated and integrated attack upon environmental problems.

The first step in seeking environmental solutions is research and development to define the problem, measure its impact and project possible remedies. Research and development is carried out continually by both industry and governmental agencies concerned with improving the environment. Much key research and development is handled by EPA's Municipal Environmental Research Laboratory. The Laboratory develops new and improved technology and systems, to prevent, treat, and manage wastewater and community sources; to preserve and treat public drinking water supplies; and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research -- a vital communications link between the research and the user community.

This document provides an outline of technical information that potentially could be used to evaluate long term remedial action plans for controlling or treating wastes or leachates at uncontrolled hazardous waste sites. It is not a design manual nor does it contain rules or regulations pertaining to remedial actions.

The intended audience for this document includes those involved in the review of preliminary engineering reports or formal designs of remedial actions at the waste sites.

Francis T. Mayo, Director
Municipal Environmental Research Laboratory

ABSTRACT

There are four major exposure pathways for uncontrolled hazardous waste disposal sites:

1. Groundwater/leachate;
2. Surface water;
3. Contaminated soils and residual waste; and
4. Air.

Remedial action technologies are designed to reduce exposure to humans and the environment to acceptable levels by either containing hazardous materials in place or removing the intrinsic hazard by decontaminating or physically removing the hazardous substances.

This report contains information on over 50 remedial action technologies. A brief description, status, factors for determining feasibility and reliability, principal data requirements, and basic information for cost review are given for each technology. In addition a general discussion of the major pathways and associated remedial approaches and of monitoring techniques has been included.

This report was submitted in fulfillment of Contract No. 68-01-5949 by Arthur D. Little, Inc. under the sponsorship of the U.S. Environmental Protection Agency. It covers the period October, 1981 to June, 1982, and work was completed as of December, 1982.

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ACKNOWLEDGMENTS

Arthur D. Little, Inc. (ADL) prepared this document for the EPA's Office of Research and Development (ORD) in fulfillment of Contract No. 68-01-5949 Task Order No. 13. Ms. Wendy Davis-Hoover and Mr. Herbert Pahren of MERL were Project Officers. Dr. John R. Ehrenfeld, ADL's Project Manager, and Mr. Jeffrey M. Bass were the principal contributors and editors. Mr. Alan Preston and Dr. William Tucker were also principal contributors. Other contributors include Ms. Marie Chung, Mr. Anthony Colella, Dr. Waren Lyman, Ms. Pamela McNamara, and Ms. Leslie Nelken. Mr. Donald Sanning, Municipal Environmental Research Laboratory, Cincinnati, Ohio and Mr. Richard Stanford, Office of Emergency and Remedial Response (OERR) are acknowledged for their direction of and valuable contributions to this report.

A peer review of the final draft was carried out by individuals associated with: 1) Illinois Institute of Technology; 2) NUS Corporation, PEC Division; 3) U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Grounds; 4) Chemical Manufacturers Association; 5) JRB Associates; and 6) Office of Emergency and Remedial Response, USEPA. As a result of the comments the document was changed, as appropriate. The helpful suggestions of these reviewers are gratefully acknowledged.

SECTION 1

INTRODUCTION

The development of remedial action plans and the ultimate implementation of those plans follows a series of steps set out in the National Contingency Plan (NCP), as described in more detail in Part 1.1, below. Early in the process, alternative technological approaches are first identified and then screened through a net of increasing stringency regarding cost and effectiveness. The U.S. Environmental Protection Agency (EPA) has developed a substantial body of information on the various technological alternatives, most recently culminating in the publication "Handbook for Remedial Action at Waste Disposal Sites." The Handbook contains extensive information about the many potential technologies and is organized to assist planners and engineers in selecting and weeding out appropriate approaches.

As the plans evolve and get closer to implementation, they must be examined for technical and economic feasibility and conformance with the guidelines in the NCP. The evaluation process implied is carried out by many parties: the EPA, state agencies, responsible disposers and facility operators, and the public at large. This report has been prepared to support this evaluation. Data on the same large set of potential technologies contained in the Handbook above are organized to assist reviewers in determining if the engineers and designers have used reasonable, conventional data and assumptions in the development process. This publication is not a design manual although, where practical, simple formulas and other information which designers generally use are included as a basis of comparison and checking.

The primary sources of the data include the series of federal publications known as "Technical Resource Documents" (TRDs), and data from several recent EPA projects on remedial activities at hazardous waste sites. One objective of this project was to make information in the TRDs available and useful to all participants in remedial action activities at hazardous waste sites. A limited, general review of the literature and state-of-the-art was carried out. The additional information was included to enhance the data from the TRDs and to complement them, particularly with regard to cost. Though this report is aimed primarily at cleanup activities involving permanent remedy, several of the technologies described here may also be used in emergency settings.

1.1 BACKGROUND

The Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA, also commonly known as Superfund), was passed late in 1981 to provide for (1) cleanup and emergency response for hazardous substances released into the environment, and (2) cleanup of inactive hazardous waste disposal sites. Section 105 of the Act directs the President to prepare a National Contingency Plan (NCP) to establish procedures and standards for responding to releases of hazardous substances. The NCP must include, among other things, methods for evaluating (including analyses of relative cost) and remedying any releases or threatened releases of hazardous substances, and means of assuring that remedial measures are cost effective.

After receiving comments on several drafts, EPA published the NCP in final form July 16, 1982 (40 CFR 300). The NCP describes procedures to develop and implement plans for remedying releases of hazardous substances. The NCP implements requirements in CERCLA and in the Clean Water Act (CWA). The NCP process, briefly summarized below, incorporates a number of judgements and decisions based on technical grounds.

These judgements and decisions occur at several steps along the process and are made by the lead agency (EPA or a state depending on the existence and nature of the agreement between EPA and the state), private responsible parties developing remedial action plans, consultants and engineers supporting the above interests, and other interested parties. This guide is designed to furnish technical information to support the NCP process and to assist those involved in making judgements and decisions.

Other documents have been prepared to support the process. In particular, as noted in the preamble to the NCP, " ... the EPA has developed a technical handbook which can be utilized along with this section of the NCP (300.70) to provide more technical information on the circumstances and types of releases in which these methods may be successfully employed." The manual is entitled "Handbook for Remedial Action at Waste Disposal Sites." This guide complements the Handbook and is oriented toward the evaluation of conceptual designs, rather than toward developing the designs. The Handbook is frequently referenced below.

This report also draws extensively on the TRDs. As part of its activities under a related act, (The Resource Conservation and Recovery Act of 1976, or RCRA) the EPA has prepared a series of publications, the TRDs, to support the permitting process required by this legislation. The TRDs describe current technologies in several broad categories related to hazardous waste disposal facilities (landfills, surface impoundments, and land treatment facilities). Many of the technologies for use at controlled hazardous waste disposal sites are applicable to remedial activities at uncontrolled, inactive sites. The TRDs represent a broad source of information that informally supports activities under the NCP for evaluating, planning, and implementing actions at uncontrolled sites.

The TRDs have a specific role in the RCRA process. They are designed to assist permit writers in arriving at a logical, well defined and well documented decision. With respect to remedial activities, they serve only as a potential source of information to the participants in the process. This report gives them easy access to the information contained in the TRDs and makes these documents more useful to them.

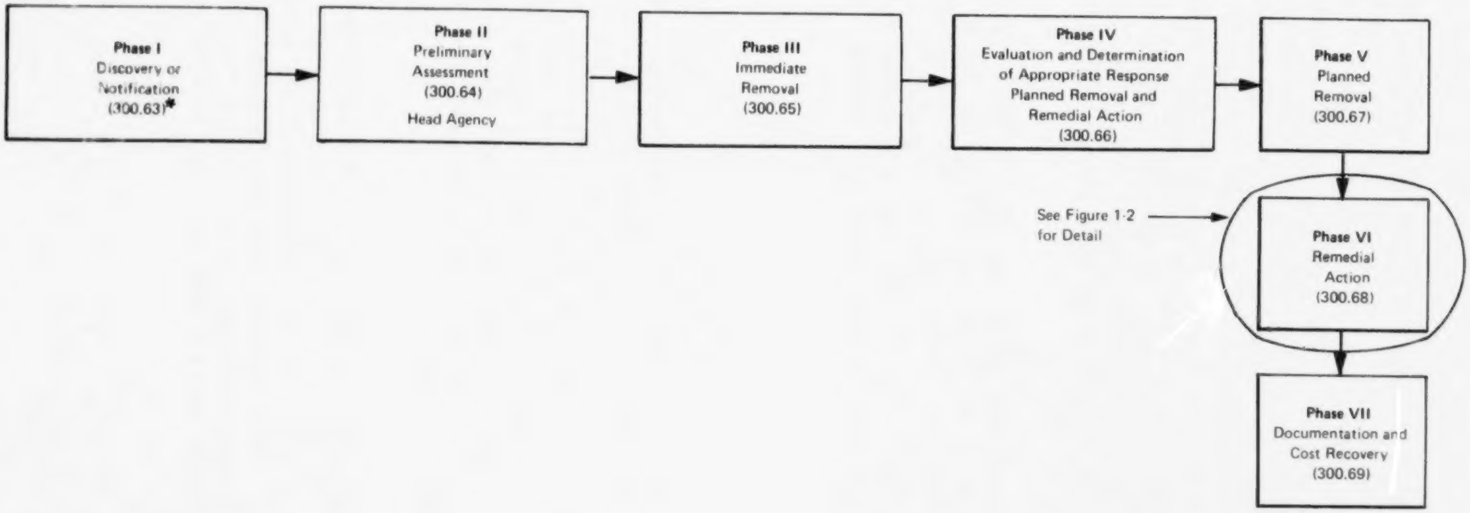
1.2 THE NCP PROCESS

The key parts of the NCP bearing on remedial action are contained in Subpart F. Subpart F identifies the state role (Section 300.62) and a phased procedure for responding to the release of hazardous substances (Sections 300.63 to 300.70). Figure 1-1 illustrates the flow of the phases. The major focus of this report is on Phase VI - Remedial Action (Section 300.68). Figure 1-2 illustrates the Phase VI process in detail and indicates the steps associated with technical criteria for which the information in this document has been developed and organized.

The first several steps are designed to elucidate the nature of the problems at a site, to determine the major courses of action, and to develop a series of potentially cost-effective alternatives dictated by those actions. The latter steps, beginning with the initial screening of alternatives, are designed to select the cost-effective alternative using the set of criteria specified in the NCP.

FIGURE 1-1

HAZARDOUS SUBSTANCE RESPONSE SEQUENCE (40 CFR PART 300)


Phase I
Discovery or
Notification
(300.63)*
Phase II
Preliminary
Assessment
(300.64)
Head Agency
Phase III
Immediate
Removal
(300.65)
Phase IV
Evaluation and Determination
of Appropriate Response
Planned Removal and
Remedial Action
(300.66)
Phase V
Planned
Removal
(300.67)
See Figure 1-2
for Detail
Phase VI
Remedial
Action
(300.68)
Phase VII
Documentation and
Cost Recovery
(300.69)

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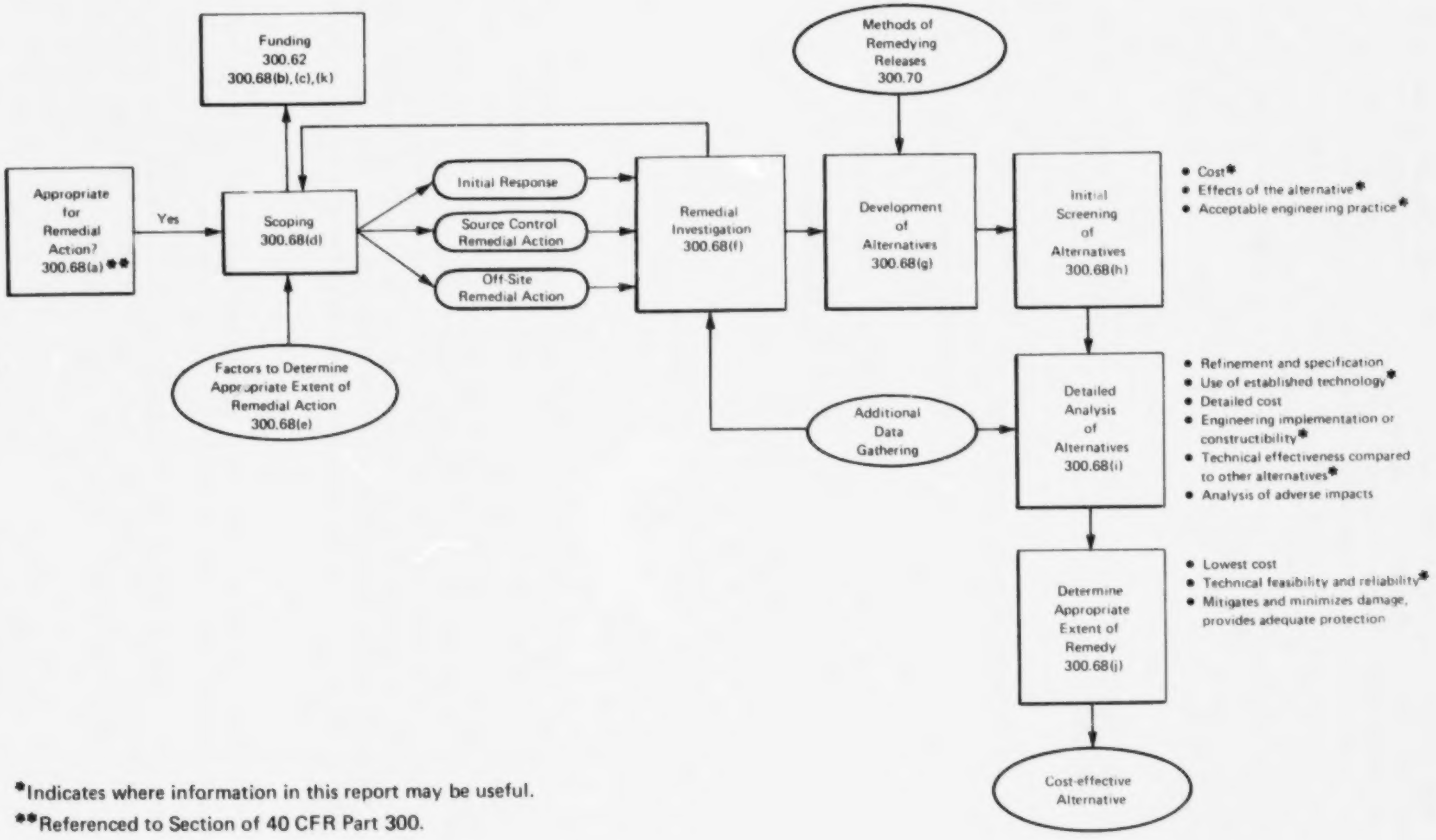
*Refers to the section of the NCP in 40 CFR part 300.

FIGURE 1-2

DETAILED SEQUENCE–PHASE VI–REMEDIAL ACTION (40 CFR PART 300.68)


Appropriate for Remedial Action? 300.68(a)**
Yes
Funding 300.62 300.68(b), (c), (k)
Scoping 300.68(d)
Factors to Determine Appropriate Extent of Remedial Action 300.68(e)
Initial Response
Source Control Remedial Action
Off-Site Remedial Action
Remedial Investigation 300.68(f)
Methods of Remedying Releases 300.70
Development of Alternatives 300.68(g)
Additional Data Gathering
Initial Screening of Alternatives 300.68(h)
• Cost*
• Effects of the alternative*
• Acceptable engineering practice*
Detailed Analysis of Alternatives 300.68(i)
• Refinement and specification
• Use of established technology*
• Detailed cost
• Engineering implementation or constructibility*
• Technical effectiveness compared to other alternatives*
• Analysis of adverse impacts
Determine Appropriate Extent of Remedy 300.68(j)
• Lowest cost
• Technical feasibility and reliability*
• Mitigates and minimizes damage, provides adequate protection
Cost-effective Alternative

*Indicates where information in this report may be useful.

**Referenced to Section of 40 CFR Part 300.

The criteria include several that are related to technical features of the conceptual design in relationship to site-specific characteristics (the factors identified with an asterisk in Figure 1-2). Judgements as to the degree which proposed plans conform to the criteria must be based on project-specific designs and analyses. But there are a number of general, technology-specific data and engineering considerations which can be used to evaluate the plans, to determine their appropriateness, and to ensure that they have been developed from sound engineering principles using reasonable cost estimates.

More specifically, this guide provides data to support the analysis and evaluation of:

- Feasibility, including:
    - acceptability (relevance to the particular project)
    - implementability or contructibility
- Effectiveness, including reliability
- State of Development
- Cost

1.3 REPORT CONTENTS

Section 2 describes general approaches to remedy problems in five media that can become contaminated by hazardous substances released at an uncontrolled site. The media are groundwater/leachate, surface water, soil, waste, and air. Sections 3 and 4 describe individual technologies and engineering methods. Section 3 describes technologies for the physical control and containment of hazardous constituents in the five media above. Section 4 describes treatment technologies for leachate, waste, and contaminated soil. Information in Section 3 and 4 is presented in the following format:

- Description--A brief, qualitative discussion of the technology and the principles on which it is based.
- Status--A measure of the availability of the technology and degree to which it has been demonstrated for hazardous waste remedial actions. Conventional, demonstrated means

the technology is widely used and has been applied successfully at uncontrolled sites or under equivalent circumstances. Conventional, undemonstrated refers to technologies in general use, but which have yet to be applied to an uncontrolled site or under sufficiently similar circumstances. Developmental refers to techniques currently in the later stages of development but not yet generally available. Some of the developmental methods are being tested at uncontrolled sites. Conceptual refers to technologies described in the literature as possibilities or as yet in early (lab or pilot) stage of research and development.

- Feasibility and Effectiveness--A discussion of the technical factors important in understanding and reviewing the technology. This part gives background necessary for evaluating technology design plans and identifies areas of particular concern. For example, the effect of waste constituents on backfill and slurry materials is critical to the effectivenss of a slurry wall. The contents of this part vary considerably from technology to technology reflecting the complexity of the technology and the sources of information used in preparing this report. This part also contains a short discussion of special precautions to be taken in using or of limitations of the technology being discussed.

- Design Basis--A summary of the major factors which determine the performance of treatment technologies. This part, which is unique to Section 4, is used for the convenience of the reader to separate basic design information from the technical concerns of implementing leachate treatment technologies. Where possible, equations relating design parameters to desired performance and site conditions are provided in summarized form. Otherwise, the relationships are described in qualitative terms.

- Principal Data Requirements--The principal site-specific data necessary for the design of the technology are noted. The data noted must be obtained in the site investigation or in laboratory based studies. The evaluation criteria or performance-related factors most directly related to each major data requirements is noted in parentheses following the data item. A summary of the data requirements common to all of the technologies in a section is provided at the beginning of Sections 3 and 4. The discussion for each technology lists the primary data concerns, expands on the summary table, and incorporates other important data needs. In addition, Table 3-2 at the beginning of Section 3 summarizes some of the conventional sources of these data.

- Elements of Cost Review--Information for analyzing technology cost estimates. Each cost discussion is divided into three parts. Components lists the major components of cost, including those which involve initial construction and capital costs, and those which involve ongoing operation and maintenance (O&M) costs. Major Factors lists the characteristics of the technology as designed for a given site (e.g., size, material availability, pretreatment requirements) that most affect overall cost. Data provides information on unit and total costs associated with the technology. Cost data provided has been updated from available sources to 1982 dollars using the following conventional indices:

Marshall & Stevens Installed Equipment	739 (1st Qtr. 1982)
Engineering News Record - Construction	3821.79 (6/17/82)
Engineering News Record - Building Cost	2227.66 (6/17/82)
Chemical Engineering Plan Construction	311 (1st Qtr. 1982)
EPA Sewage Treatment Plan Construction	412
Hourly Earning Index (Chemical Eng'g Progress)	19.60

Other assumptions used in determining 1982 costs include:

- Electricity Costs: $.04/Kwhr unless otherwise noted.

- Items such as contingency or overhead allowance, which are highly variable, are generally not included in the estimates. Tables 3-40, 3-42, and 4-39, however, do include contingency and overhead allowance to show how these items can affect cost.

- Items such as laboratory and field testing, technology design or other preliminary analyses are generally not included in cost estimates.

In general, data in this part are highly variable reflecting differences in sources used. Many of the costs for leachate treatment technologies, for example, are based on information developed in industrial or municipal settings at much larger scale than may be required for remedial action. Cost information, therefore, should be used only for rough estimating purposes, unless the actual site condition closely resemble the assumed cost basis.

Section 5 presents a general discussion of monitoring techniques for use during remedial activities and during the post-closure custodial period. A discussion of monitoring wells in the format of Sections 3 and 4 is also provided.

The report's organization by media was chosen to help direct attention to the group of technologies most relevant to the problems identified at a particular site. The technology discussions present information in a concise format, relying heavily on figures, tables, and lists to allow easy access to information needed to evaluate remedial action technology plans.

1.4 DESCRIPTION OF THE TECHNICAL RESOURCE DOCUMENTS

The eleven TRDs now available, either in draft or final versions are briefly described below. These reports are referred to throughout as TRD 1, TRD 2, etc. The formal references appear in each paragraph below. The descriptions marked with an asterisk have been taken verbatim from TRD 7.

TRD 1*-- The manual "Evaluating Cover Systems for Solid and Hazardous Waste" is intended for use by the regional offices in their evaluation of applications from owners/operators of solid and hazardous waste disposal areas. More specifically, it is a guide for evaluation of closure covers on solid and hazardous wastes. The manual provides a guide to the examination of soil, topographical and climatological data, closure cover evaluation, recommendations, and a discussion of post-closure plans (Lutton, 1980).

TRD 2*-- The document "Hydrologic Simulation on Solid Waste Disposal Sites" presents an interactive computer program for simulating the hydrologic characteristics of a solid and hazardous waste disposal site operation. Using minimal input data from the user, the model will simulate daily, monthly, and annual runoff, deep percolation, temperature, soil-water, and evapotranspiration. The manual provides sufficient information and commands so that an inexperienced user may perform the operation. The model is designed for conversational use -- that is, interaction with the computer is direct and output is received immediately (Perrier and Gibson, 1980).

TRD 3*-- The "Landfill and Surface Impoundment Performance Evaluation" manual is intended to provide guidance in evaluating designs to predict the movement of liquids through and out of a surface impoundment and landfill. It includes a discussion of acceptable operating procedures, design configurations, analysis procedures, and techniques for interpretation of results as they apply to impacts on ground and surface water (Moore, 1980).

TRD 4*-- "Lining of Waste Impoundment and Disposal Facilities" provides information on performance, selection, and installation of specific liners and cover materials for specific disposal situations, based upon the current state-of-the-art of liner technology and other pertinent technology. It contains descriptions of wastes and their effects on linings; a full description of various natural and artificial liners; liner service life and failure mechanisms; installation problems and requirements of liner types; costs of liners and installation; and tests that are necessary for preinstallation and monitoring surveys (Matrecon, Inc., 1980).

TRD 5*-- The manual "Management of Hazardous Waste Leachate" presents management options that a permit writer or hazardous waste landfill operator may consider in controlling a leachate problem. The manual contains the following: a general discussion of leachate generation; a section on leachate composition providing the permit writer with possible guidelines for determining the relative hazard of a particular leachate; a discussion of five potential management options for the off-site treatment of leachate or the on-site treatment of hazardous waste; and a discussion of treatment technologies that, on a laboratory scale, have demonstrated reasonable success in treating leachate (TSA Division of Michael Baker, Inc., 1980).

TRD 6*-- The "Guide to the Disposal of Chemically Stabilized and Solidified Wastes" provides guidance to waste generators and regulatory officials in the use of chemical stabilization/solidification techniques for limiting hazards posed by toxic wastes in the environment. The current state and performance of hazardous waste disposal and long-term storage techniques are discussed. In addition to a discussion of major chemical and physical properties of treated wastes, a list of major stabilization/solidification technology suppliers and a summary of each process are provided (Malone et al., 1980).

TRD 7*-- The manual "Closure of Hazardous Waste Surface Impoundments" describes and references, the methods, tests, and procedures involved in closing a site in such a manner that (a) minimizes the need for further maintenance, and (b) controls, minimizes, or eliminates, to the extent necessary to protect human health and the environment, post- closure escape of hazardous waste, hazardous waste constituents, leachate, contaminated rainfall, or waste decomposition products to ground water, surface waters, or the atmosphere. Problems that have been overlooked in abandoned impoundments and have caused environmental degradation are discussed. The techniques involved are pertinent to closing an impoundment either by removing the hazardous wastes or by consolidating the waste on site and securing the site as a landfill. Technical criteria for implementing the closure, specifically those regarding aspects substantially different from a landfill, are given. Relevant literature or procedures are documented for more in-depth review as necessary (Wyss, et al., 1980).

TRD 8*-- The document entitled "Hazardous Waste Land Treatment" presents a dynamic design approach for land treatment facilities. This design strategy is based upon sound environmental considerations and is structured into a total system approach. The manual discusses site assessment procedures aimed at selecting acceptable locations. This site assessment procedure consists of (1) technical consideration of site characteristics and (2) sociographical considerations of area land use. In addition, the manual describes specific land treatment components and explains why they are important to an effective design. These components include: the land treatment medium, hazardous waste stream, preliminary tests and pilot experiments on waste-soil interactions, facility design and management, monitoring, changing wastes, contingency planning, and site closure (K.W. Brown & Assoc., 1980).

TRD 9-- "Soil Properties, Classification and Hydraulic Conductivity Testing" is a compilation of available methods for the measurement of saturated and unsaturated hydraulic conductivity (permeability) of soils. Seventeen methods in the categories of laboratory, field, and miscellaneous procedures are discussed. Background information on relevant soil properties and classification systems is also given (Roberts and Nichols, 1980).

TRD 10-- The "Solid Waste Leaching Procedures Manual" addresses the prediction of leachate mixing and movement in groundwater. In particular, the effect of groundwater mixing on leachate contaminant concentrations, the direction and manner of leachate plume travel, and the appropriateness of various groundwater models are considered. Two approaches for use by the permit writer are presented: the Site Rating System, a qualitative and parametric approach; and the Plume Rating System, a more quantitative approach (Pettyjohn et al., 1980).

TRD 11-- The manual "Evaluation of Closure and Post-Closure Care Plans for Hazardous Waste Landfills" describes the general factors that should be considered in preparing and evaluating landfill closure plans. Current state-of-the-art knowledge with respect to the technologies that are applicable to closure and post-closure of hazardous waste landfills is presented. A synopsis of important regulations and a comprehensive example for closure and post-closure care of a hypothetical landfill are also given (SCS Engineers, 1982).

SECTION 2

PRINCIPAL MEDIA AND ASSOCIATED REMEDIAL APPROACHES

Developing a cost-effective remedial response for uncontrolled releases of hazardous wastes requires knowledge of the settings in which various problems occur and of the options to deal with those particular problems. This chapter describes the major types of problem settings, identifies the most significant site-specific features bearing on the choice of remedy and describes the major classes of remedial actions. Sections 3 and 4 present more detailed information and data describing the many individual remedial techniques. Figure 2-1 depicts the environmental setting for a generalized uncontrolled disposal site, located above the water table. Potential pathways to human and ecological receptors are shown in Figure 2-2. A major variant would place the waste mass below the water table, in which case the leachate plume and groundwater are always coincident. The exposure pathways are essentially the same in both cases, but the applicability of a number of potential remedies is quite different in the two cases.

This report focuses on remedying hazards due to the migration or potential migration of toxic materials from the disposal site through a series of environmental pathways. Mitigating hazards due to the corrosivity, ignitability and reactivity characteristics of waste can also be accomplished by some of the treatment methods discussed; corrective technologies for these types of problems (corrosivity, etc.) plus potential exposure by direct contact are often included in emergency response programs preceding remedial actions and are described in the literature on that subject. Emergency response is not discussed in detail here; the emphasis is on long-range remedial actions. Figure 2-1 indicates that potential, hazards at uncontrolled disposal sites can and generally do involve multiple media. As a result, the remedial action programs must include an integrated attack on the underlying problems. Remedial action can follow two main approaches:

1. Contain the hazardous materials, preventing exposure to human or ecological species.

FIGURE 2-1
ENVIRONMENTAL PATHWAYS FROM A GENERALIZED HAZARDOUS WASTE SITE

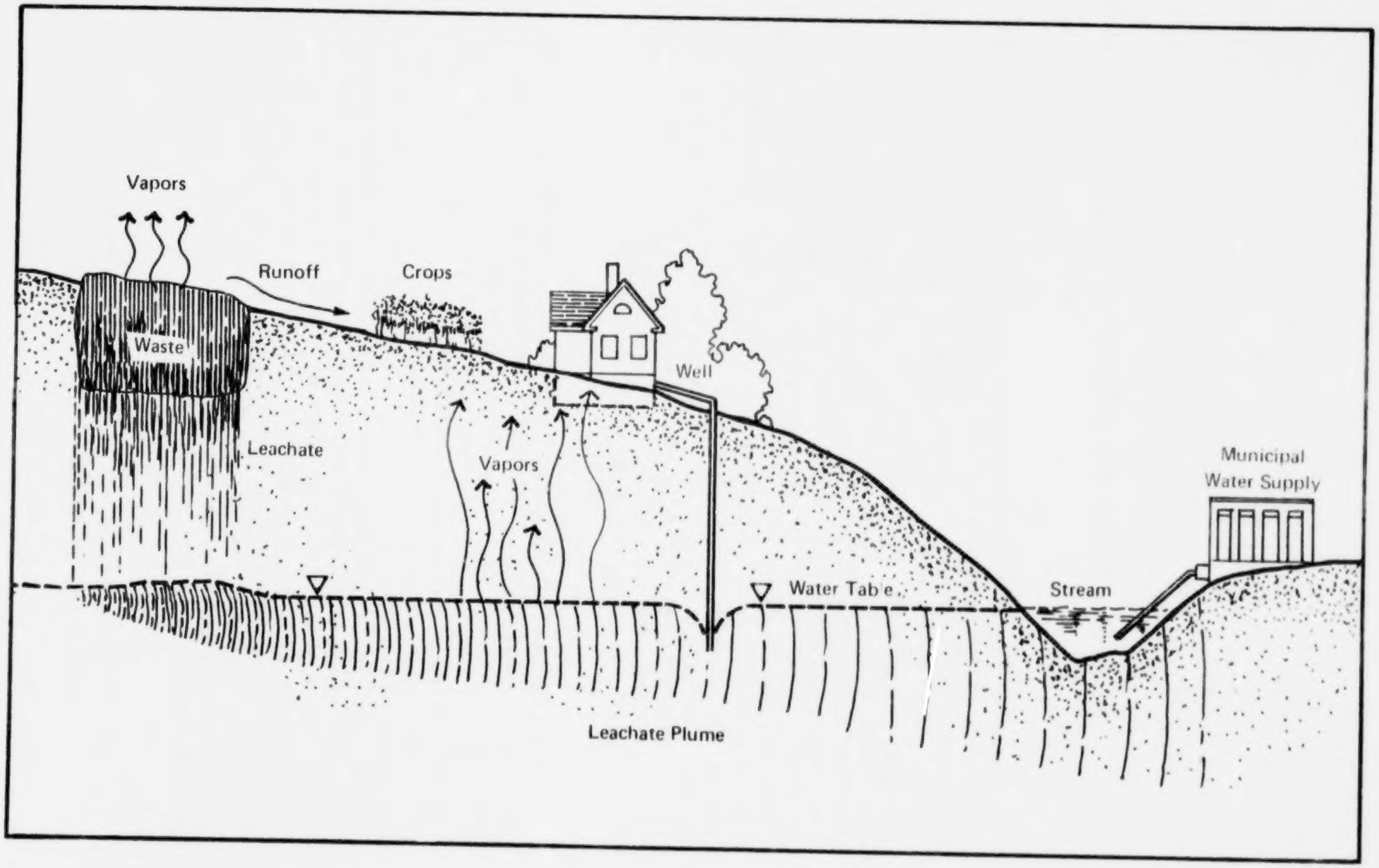
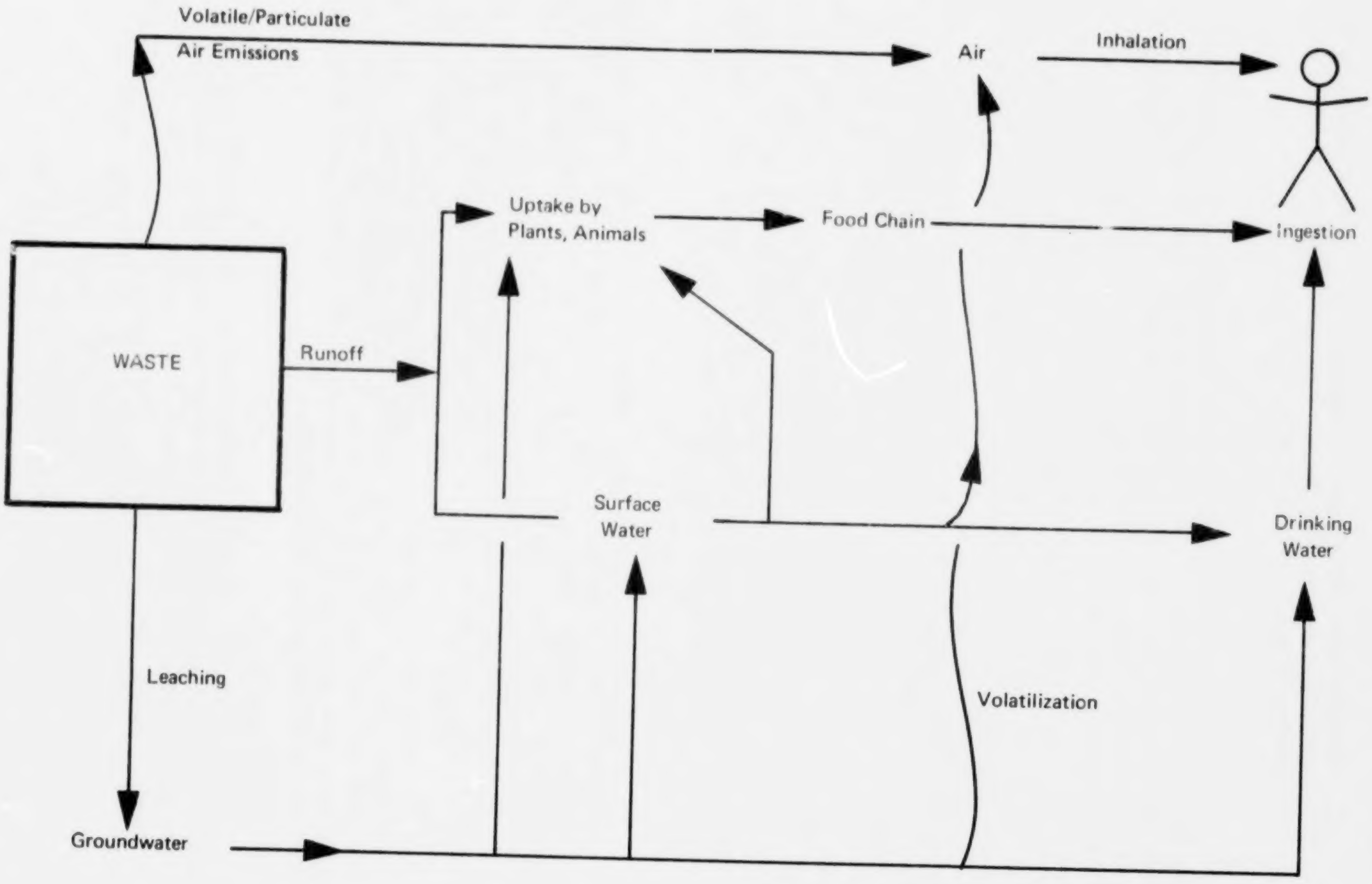

Vapors
Runoff
Crops
Waste
Well
Leachate
Vapors
Municipal Water Supply
Water Table
Stream
Leachate Plume

FIGURE 2-2

SCHEMATIC DIAGRAM OF EXPOSURE PATHWAYS


Volatile/Particulate
Air Emissions
Air
Inhalation
WASTE
Runoff
Uptake by
Plants, Animals
Food Chain
Ingestion
Surface
Water
Drinking
Water
Leaching
Volatilization
Groundwater

2. Remove the intrinsic hazard; i.e., decontaminate or physically remove the hazardous substances at the source or in the contaminated pathway.

The first approach can reduce hazards to an acceptable level, in the short-run, but may leave questions of the long-run risks arising from failures in the containment system (for example, leaks in a liner) or from natural phenomena (for example, earthquakes). Physical removal of hazardous materials to another site provides a long-term, essentially permanent, solution at the uncontrolled site, but transfers many of the inherent problems to the new site, in addition to creating new risks due to removal and transportation. Since hazardous waste treatment, disposal and storage facilities must now operate under RCRA and perhaps state and local regulations as well, the potential risks to human health and the environment should be reduced to acceptable limits at the new site. Decontamination at a site, if effective, can provide the same long-term remedy without transferring the hazards off-site. But this approach may be expensive and difficult to apply at sites with extensive soil and water contamination. In many cases, a combination of the foregoing two general approaches may be the most effective; e.g., a containment system to limit the extent of environmental contamination and potential exposure, and a long-term decontamination system to eliminate the source of the hazard.

This report, by design, treats problems and remedial action technologies in a general sense, organized as noted below by major exposure pathways and, further, by broad classes of potentially applicable remedial approaches. The data and descriptive information presented in this introductory chapter and in the subsequent discussions of individual technologies are generalized and do not reflect the variability of problems from site-to-site nor the particular design configuration appropriate for a given site. There will be many site-specific exceptions to the general considerations presented below that may render a usually appropriate technology impractical or ineffective and, vice versa, may promote the attractiveness and feasibility of concepts not usually associated with the type of problem being addressed.

The remedial action technologies are organized, both in this section and also in the following two sections, on Control Technologies and Treatment Technologies, according to the type of exposure pathway with which each technology is most conventionaly associated. Four major exposure pathway classes used are:

1. Groundwater/Leachate;

2. Surface Water;
3. Soil and Residual Waste Materials; and
4. Air.

Contaminated sewer and water lines, additional pathways found at some sites, are not discussed in this report. Each of the four classes is described in the following sub-sections.

No site is likely to correspond exactly to any of the environmental settings described below. Many problems involve combinations of contaminated pathways. Geological and hydrogeological characteristics, particularly, are highly site-specific. As a consequence, project-by-project analyses are essential in the development and evaluation of remedial action alternatives. The general data in this report can be supplemented in the future with documentation of actual experience at sites. That kind of information is now beginning to appear in the general engineering literature at an increasing rate.

2.1 GROUNDWATER/LEACHATE

Groundwater contamination is the most commonly encountered problem at existing uncontrolled hazardous waste disposal sites. Groundwater contamination results from the migration of leachate which is defined under RCRA as "any liquid, including any suspended components in the liquid, that has percolated through or drained from hazardous wastes." (Fed. Reg. 45, 33075, May 19, 1980).

Groundwater contamination may occur at a wide variety of waste management facilities and disposal sites including:

1. storage and treatment facilities;
2. landfills;
3. surface impoundments;
4. mines;
5. surface waste piles; and
6. land treatment facilities.

Figure 2-3 illustrates potential patterns of leachate migration and ensuing groundwater contamination that can occur relative to the water table.

Exposure to the pollutants in leachate can occur in a variety of ways, as shown in Figures 2-1 and 2-2, and described below.

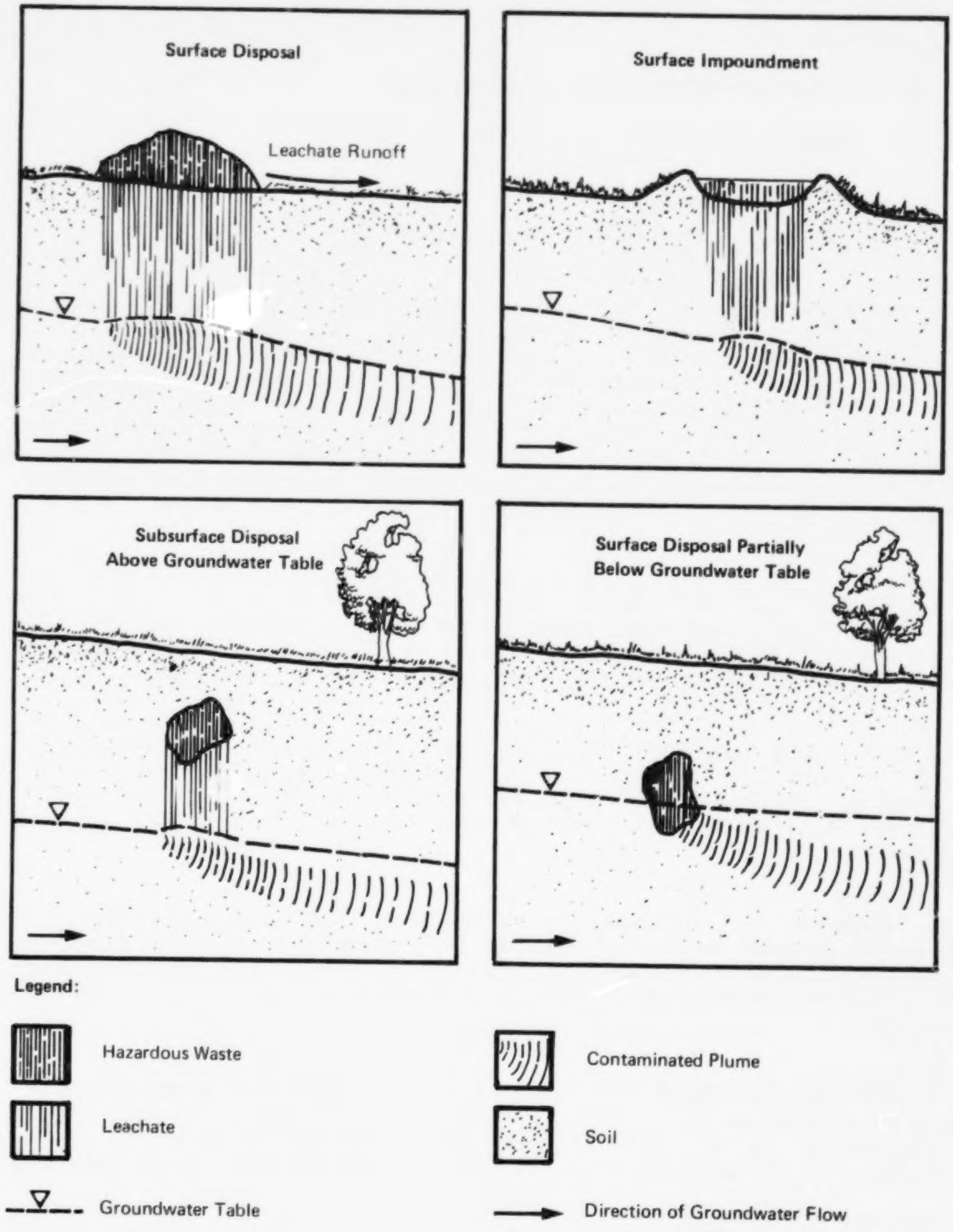
1. The leachate plume in the groundwater may be drawn into wells used for drinking water supply, crop irrigation, food processing, etc.;
2. The leachate plume may intersect a surface water body (for example, a reservoir or river) which, besides supporting biota (thus affecting the food chain), may serve as a potable water supply;
3. Leachate from a surface dump may appear in surface runoff which may come in direct contact with humans, may contaminate surface crops, or pollute nearby surface waters; or
4. Vapors from volatile chemicals in the leachate may diffuse up through the soil surface and lead to exposure via inhalation; entry of vapors directly into the basements of buildings is of particular concern.

Data describing the EPA initial list of high-priority remedial action sites identifies groundwater contamination in two-thirds of the cases and surface water contamination in over half of the cases.

The leachate may contain portions of almost every chemical present in the hazardous waste. If the original waste contains a liquid component, it may drain from the waste and -- to the extent that it has limited water solubility -- create a "second phase" in the leachate. Such immiscible liquids may, if lighter than water, spread over the surface of the groundwater table, and, conversely, may sink to the bottom layers of the aquifer, if heavier than water. Also, where two phases coexist, the driving force on and resultant flow of each fluid phase are not always the same. For example, gasoline can flow in a different direction from the groundwater over which it is spread. If the hazardous waste contains a mixture of both inorganic and organic chemicals, portions of both will be dissolved in any percolating water and show up in the leachate. Under worst case conditions, the amount dissolved may be at the solubility limit; entrainment of small particles may make the effective concentration even higher. The concentration in groundwater of certain inorganic species, especially the metals, may be more dependent upon the soil and leachate chemistry than on the form in the original waste.

FIGURE 2-3

LEACHATE MIGRATION AND GROUNDWATER CONTAMINATION


Surface Disposal
Leachate Runoff
Surface Impoundment
Subsurface Disposal Above Groundwater Table
Surface Disposal Partially Below Groundwater Table
Legend:
Hazardous Waste
Leachate
Groundwater Table
Contaminated Plume
Soil
Direction of Groundwater Flow

2.1.1 Containment Techniques

Means to contain leachate migration include:

- reduction of surface infiltration;
- upgradient diversions or barriers;
- downgradient diversions or barriers; and
- leachate and groundwater collection.

The first approach (reduction of surface infiltration) reduces the potential for leachate production and, thus, migration into the groundwater. Most leachate is generated by the action of water percolating downward through the materials deposited at a disposal site. Methods for excluding surface water, from a site, discussed below under Surface Water, also support this approach. This approach will not eliminate leachate produced by leakage of liquid components in the waste materials or produced by biodegradation but may reduce the rate at which they enter the groundwater.

The second means (upgradient diversions or barriers) prevents groundwater from contacting the waste mass or the leachate plume by rerouting the groundwater flow pattern and adjusting the level of the water table. Such techniques are used in the groundwater flow before it impinges on the site, and hence the term upgradient.

The third approach (downgradient diversions or barriers) is used to stop and contain the flow of groundwater already contaminated by leachate migration or direct contact with the waste. Groundwater pumping and treatment are typically required with this approach.

Leachate and groundwater collection, the last approach, comprises a number of techniques to intercept the leachate plume or groundwater stream and move it to a discharge where the contaminated water can be treated or disposed of under satisfactorily controlled conditions.

Appropriate remedial actions will vary with the disposal practice as discussed below. The nature of the remedial action program will depend on the location of the water table relative to the wastes. If the preliminary site investigation indicates that the wastes are above the water table, existing weather and hydrogeological data should be examined, because the water table fluctuates over time to determine if the seasonally high water table will intercept the wastes. In the absence of adequate historical data, the design should be based on additional tests at the site including soil tests and determination of color changes in stratigraphic columns.

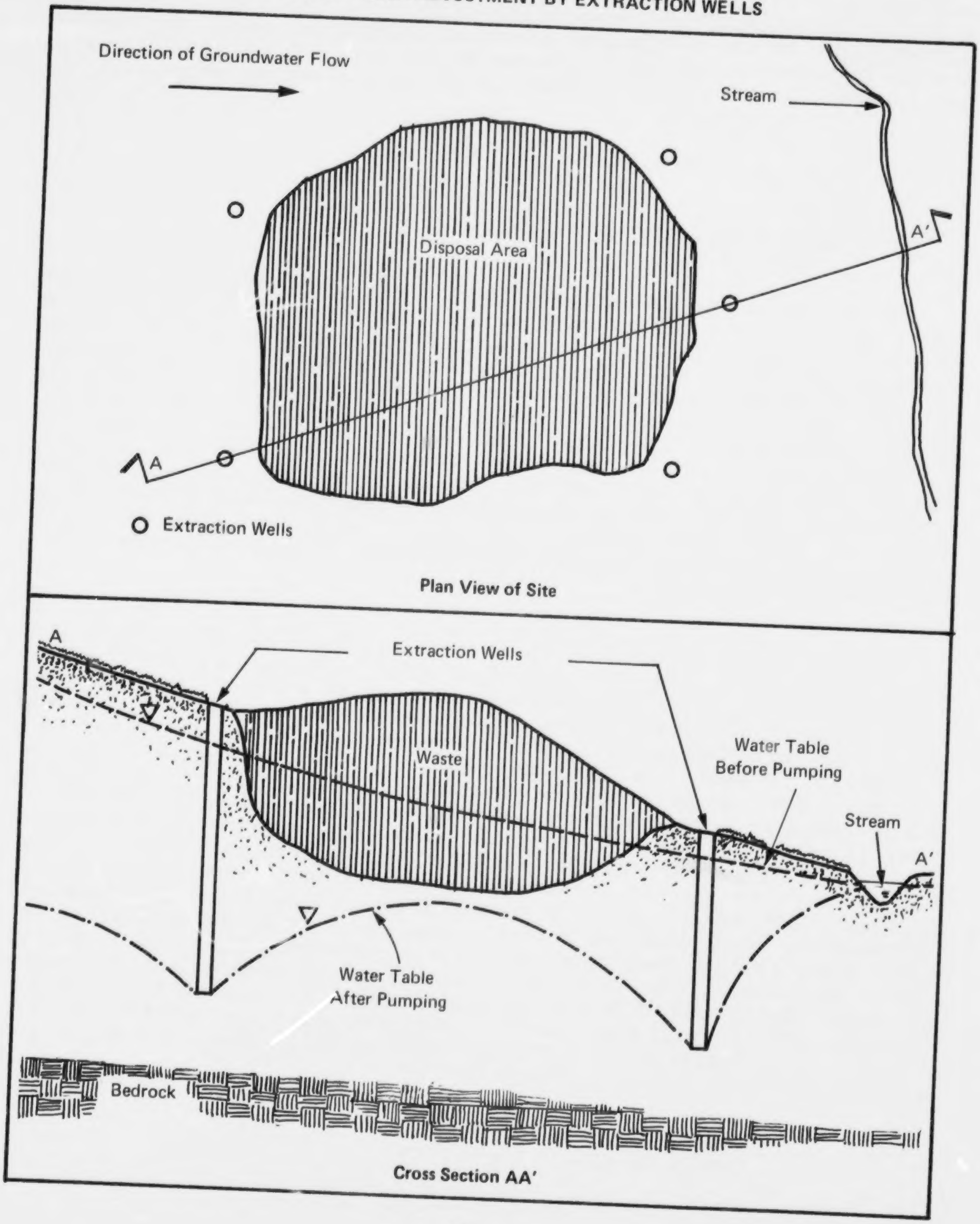
2.1.1.1 Landfills

Waste Below the Water Table

Water table (or groundwater table) adjustment, plume containment, and barriers to groundwater flow are potentially applicable remedial actions for landfills where waste has been placed below the groundwater table. The primary objective of water table adjustment, typically accomplished via groundwater extraction (pumped) wells is to lower the water table below the emplaced wastes. The objective of plume containment systems, also accomplished by groundwater extraction wells, is to reverse the downgradient movement of contaminated groundwater and collect the contaminated water. Plume containment systems must also address the treatment and related handling of the contaminated water. The principal objective of barriers is to control the movement of water either before or after it contacts the waste.

Water table adjustment by groundwater pumping can reduce the rate of leachate generation and further, of groundwater contamination. Figure 2-4 schematically illustrates a water table adjustment system. Wells are sited and pumped at rates which will lower the water table below the emplaced wastes. The specific number and placement of wells is site specific. Figure 2-4 indicates wells placed around the perimeter of the site. The wells have lowered the water table below the waste mass. At some sites it may be feasible to drill wells directly through the waste although safety considerations, or the potential for further spread of contamination, may render such an option infeasible or more costly than a periphery system. Cost-effective well system design (locations, development techniques, and pumping rates) requires thorough analysis of site-specific hydrogeologic data and engineering cost data. Water table adjustment may also be accomplished by subsurface drainage systems. Selection of a well or drain system is dependent primarily on the depth of the waste. Drains may be preferred if construction/emplacement is feasible, and wells where the depth is greater

FIGURE 2-4
WATER TABLE ADJUSTMENT BY EXTRACTION WELLS


Direction of Groundwater Flow
Stream
Disposal Area
A
A′
Extraction Wells
Plan View of Site
A
Extraction Wells
Waste
Water Table Before Pumping
Stream
A′
Water Table After Pumping
Bedrock
Cross Section AA′

Plume containment by groundwater pumping is also potentially applicable for landfills with waste below the water table. Referring to Figure 2-4, we see that a pumping system designed for water table adjustment may also be adequate for plume containment if the plume of contaminated groundwater has not migrated downgradient further than the radius of the cone of depression of the dewatering well. In this case the plume of the contaminated groundwater will flow toward the well and be withdrawn by pumping. This situation is more likely to occur for newer landfills than for fills which have accepted hazardous wastes for many years. In general, plume containment by groundwater pumping would require a well system independent of the system designed for water table adjustment.

Barriers to groundwater flow (slurry walls, grout curtains, sheet pile barriers) may also be used to isolate waste from groundwater at landfills where wastes are below the water table. The site specific conditions under which barriers might be useful are potentially so varied that it would be fruitless to try to enumerate and characterize them in a completely general way. One generic situation, placing a barrier in a shallow water table aquifer, relates to a large number of sites with groundwater problems. The following discussion about that setting serves to illustrate the most important features of barrier use. In the more general case, the existing water table which reflects the water balance and subsurface material stratigraphy at the site must be considered in estimating the effect of a barrier.

The principal effect of a groundwater barrier is to reduce substantially flow perpendicular to the barrier. If the barrier is very long (in mathematical idealization: an infinite barrier) or completely crosses the lateral extent of the aquifer and tied to impermeable strata on all sides, then the groundwater which has been intercepted by the barrier will accumulate upgradient of the barrier, causing the water table to rise. This situation is illustrated in Figure 2-5. Figure 2-5a shows the natural conditions with, for example, 10 units of water flowing parallel to the cross section. Figure 2-5b shows the situation shortly (e.g., weeks) after the barrier is emplaced. The 10 units of water continue to flow toward the barrier but practically none gets through.

The steady-state, or long-term response to the barrier emplacement will be completely dependent on localized hydrogeologic factors, and there is no generic response typical of all such sites. Figures 2-5c and 2-5d, however, represent steady-state responses which may be typical of arid and hummid sites, respectively. As the water table rises upgradient and falls downgradient of the barrier, small flow through the barrier may occur. The increased head upgra-

FIGURE 2-5-a

NATURAL AQUIFER CONDITIONS

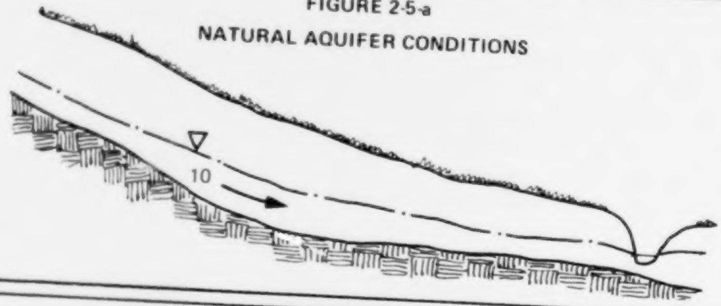


FIGURE 2-5-b

TRANSIENT RESPONSE SHORTLY AFTER BARRIER EMPLACEMENT

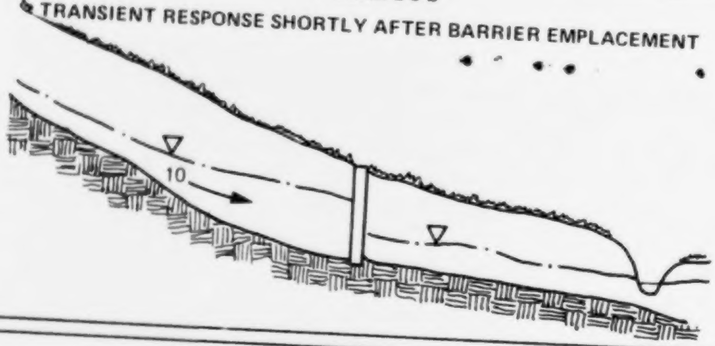


FIGURE 2-5-c

HYPOTHETICAL STEADY STATE RESPONSE IN AN ARID SETTING

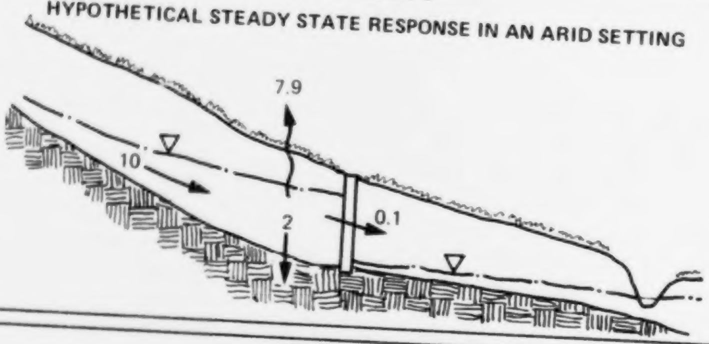
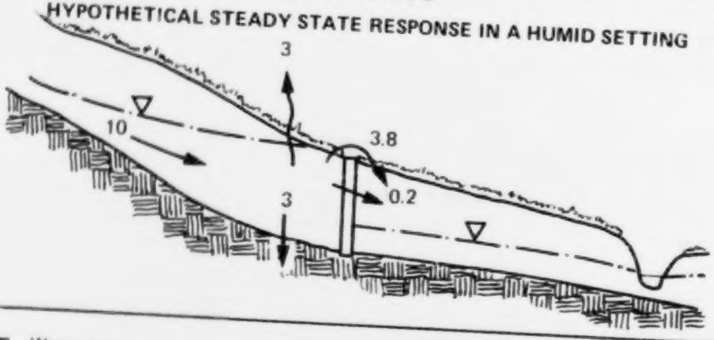


FIGURE 2-5-d

HYPOTHETICAL STEADY STATE RESPONSE IN A HUMID SETTING



— · — ▽ — · — Water table

→ Groundwater flow

dient may also force water downward through the relatively impermeable confining layer below the aquifer.

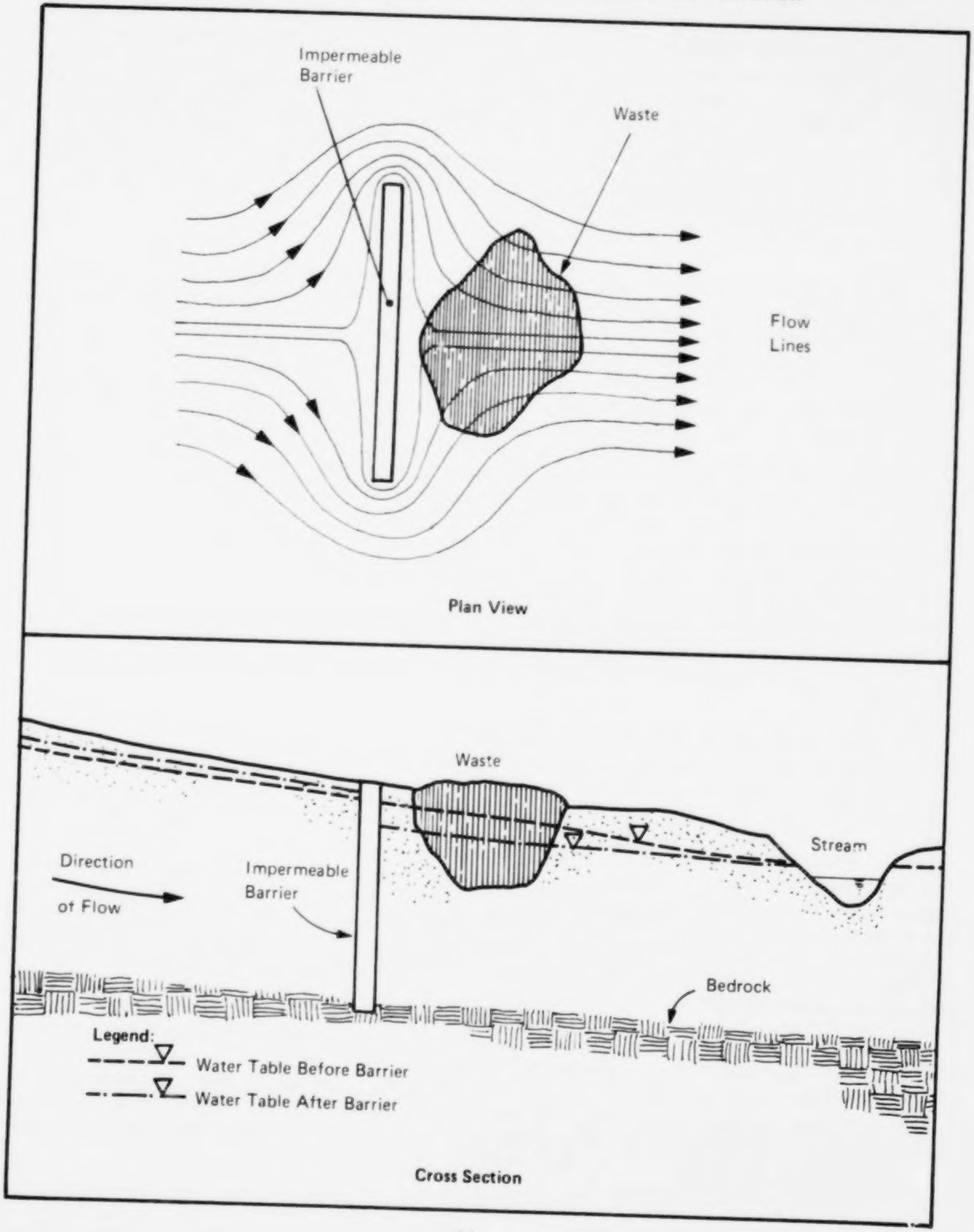
As the water table rises toward the land surface, evapotranspiration rates will naturally increase. The evaporation rate in arid climates will often be great enough to balance the natural lateral flow of water in the aquifer. The water table would equilibrate at the level (see Figure 2-5c) where the incoming lateral flow (10 units) is blanced by flow through the confining layer (2 units) plus flow through the barriers (0.1 unit) plus evapotranspiration (7.9 units).

In a more humid climate, evapotranspiration would also increase as the water table approached the surface, but often not enough to balance the lateral flow, allowing the water table to eventually rise to the surface and overtop the barrier (Figure 2-5d). Clearly, this would be a poor design, and some additional water control would be required. For example, groundwater extraction wells upgradient of the site may be necessary to remove excess groundwater. Although this is a purely hypothetical situation, many actual situations where barriers might be used in remedial action will require associated water controls such as groundwater extraction and recharge wells, surface water controls, subsurface drains, and so on. Existing and proposed uses of groundwater barriers in remedial action typically include associated groundwater controls. For example, the major slurry wall installation at Rocky Mountain Arsenal, designed for plume containment, incorporates upgradient extraction wells, a water treatment system, and subsequent downgradient injection wells (Wardell, 1981).

The idealized situation characterized by Figure 2-5 is rarely found in practical applications, because it is usually infeasible to cutoff the complete lateral extent of an aquifer, or make a barrier so long that it approaches the response of an ideal infinite barrier. Less extensive barriers--for example, upgradient of a waste disposal site--are not likely to be effective in lowering the water table since they do not prevent water from flowing around the barrier. Figure 2-6 illustrates this situation. The barrier diverts groundwater flow around it but will not cause a significant lowering of the water table downgradient of the barrier. A slight reduction in head results from viscous energy losses along the longer flow path taken by the water after it encounters the barrier. The resulting head loss immediately downgradient of the barrier will be proportional to the length of the new flow path, regardless of the shape of the barrier. This will lead to a flattening of the water table downgradient but not a substantial dewatering of the waste site. Although a very long barrier might cause a large enough head loss to dewater wastes at some sites, a very long barrier is not

FIGURE 2-6

EFFECT ON GROUNDWATER LEVEL OF UPGRADIENT BARRIER


Impermeable Barrier
Waste
Flow Lines
Waste
Direction of Flow
Impermeable Barrier
Stream
Bedrock
Legend:
Water Table Before Barrier
Water Table After Barrier

Plan View

Cross Section

likely to be less expensive than other dewatering techniques, such as pumped wells or subsurface drains. Consequently, upgradient barriers which do not intercept the full lateral extent of the aquifer are not likely to be recommended, alone, for dewatering purposes. They may be more effective when used in conjunction with surface water controls or well systems.

An alternative, and generally more effective use of barriers for dewatering wastes is to completely encircle the waste and tie into the bedrock (or other impermeable confining beds). Depending on site-specific hydrogeologic conditions, several configurations may be effective. If the barrier completely surrounds the waste and extends to bedrock (or other impermeable layer), lateral groundwater flow through the waste will be reduced to negligible amounts as shown in Figure 2-7. In arid climates or at sites with impermeable surficial material, reduction of lateral flow will eventually dewater the waste. However, in humid climates with permeable surficial soils (including permeable waste deposits), vertical infiltration may lead to a "bathtub" effect, causing high water table within the barrier which could then increase vertical flow through the waste or lateral flow through or over the barrier. Capping, pumping, or leachate collection may be required in conjuction with the barrier to mitigate this "bathtub" effect. Barriers which encircle the wastes but are not tied to an impermeable layer will reduce, but not eliminate, leachate contact with the natural groundwater as groundwater will flow around and under the barrier causing the disposal site to become a region of "stagnant" groundwater.

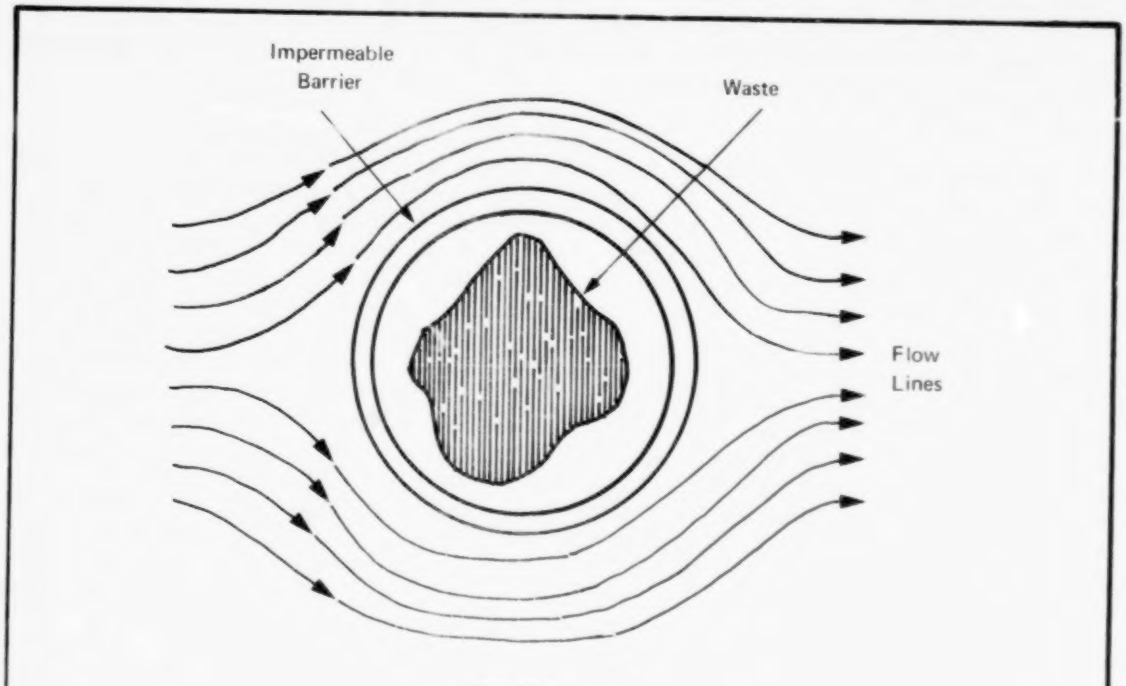
If the waste lies below the water table, it will generally be ineffective to implement controls designed to prevent leachate production without including one of the groundwater control measures. In these cases, lateral migration is often the principal water flow route through the waste. Thus capping, grading, surface sealing, surface water diversion, and other measures which may reduce surface water infiltration are not expected to have significant effect on groundwater when wastes are below the water table.

Waste Above the Water Table

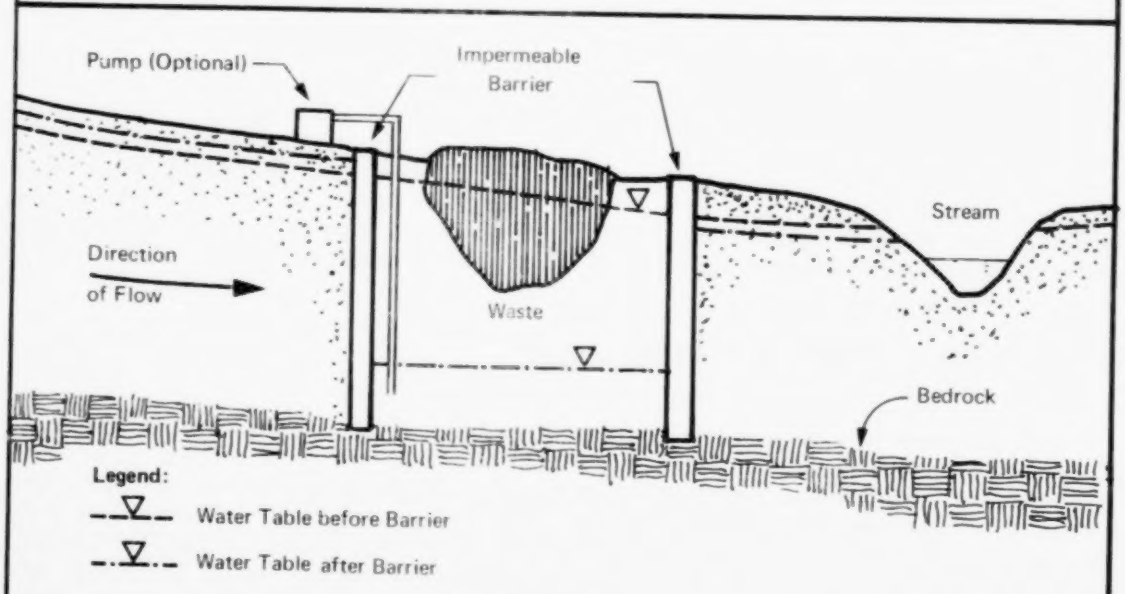
If wastes are deposited above the water table, groundwater contamination may result from infiltration of surface water downward through the wastes or by percolation of liquids associated with the waste downward to the water table. If infiltration of surface water is generating contaminated leachate, then surface water controls, such as surface seals, surface water diversions, and grading are likely to be the most cost-effective measures for reducing further contamination to groundwater. Subsurface drainage systems may also

FIGURE 2-7

EFFECT ON GROUNDWATER LEVEL OF BARRIER SURROUNDING WASTE


Impermeable Barrier
Waste
Flow Lines

Plan View


Pump (Optional)
Impermeable Barrier
Stream
Direction of Flow
Waste
Bedrock
Legend:
Water Table before Barrier
Water Table after Barrier

Cross Section

be effective in collecting contaminated leachate before it contaminates the subsurface aquifer. However, groundwater controls may also be necessary to clean up already contaminated portions of the aquifer.

2.1.1.2 Surface Impoundments

Problems at surface impoundments (often called lagoons or disposal ponds) arise principally from leakage of stored wastes or leachate through the bottom layers. In the case of unlined surface impoundments, leakage may occur due to the natural permeability of the bottom or to a more concentrated leaking area more directly connected to the underlying groundwaters. Remedial action approaches may be needed at unlined surface impoundments because of their natural tendency to leak after some period of time.

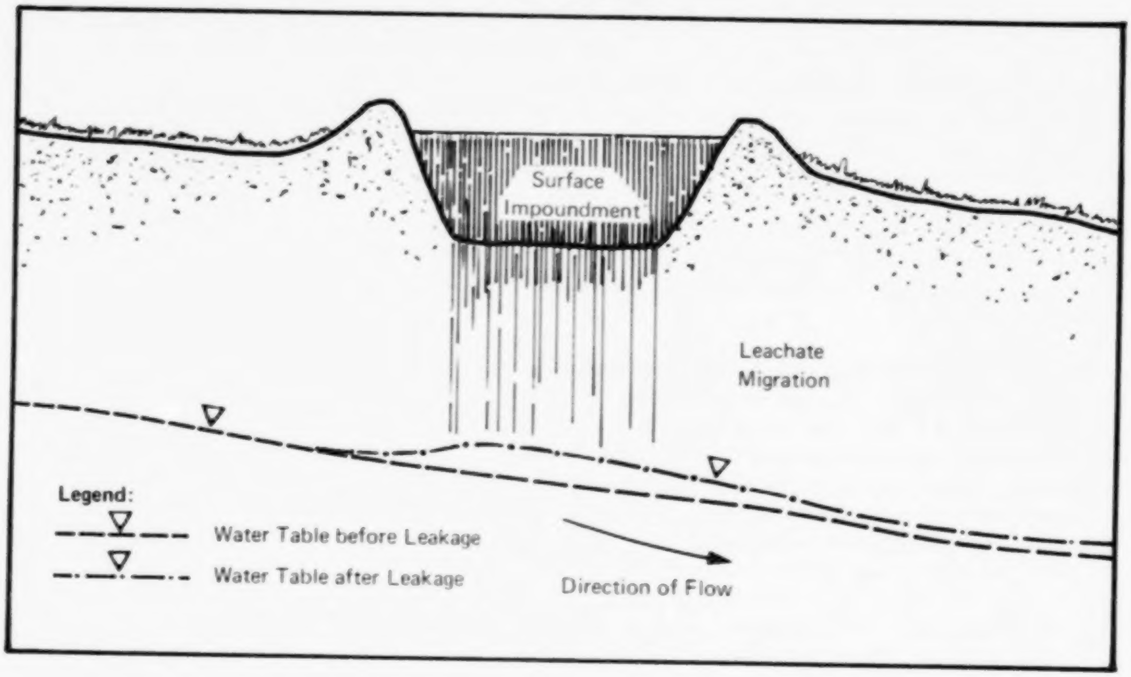
More recent surface impoundment designs incorporate liners to prevent leakage. Liners may be synthetic materials or clays of very low permeability. Even a lined surface impoundment may be a cause of groundwater contamination if the liner has been damaged either by chemical interaction with the waste or leachate, physical disturbance or improper design and installation. If a clay liner is leaking from a few isolated seepage points, it may be possible to repair the liner, perhaps by grouting. However, the technical feasibility of liner repair has yet to be generally demonstrated. Currently, it is very difficult to locate leaks unless a specific physical disturbance has been documented, so in most cases a surface impoundment with a leaky liner should be dealt with in the same way as an unlined surface impoundment.

Surface impoundments may be further categorized as being above or below the water table. If a surface impoundment is above the water table, leakage will create a mounding of the water table directly below it as the leachate migrates downward, skewed in the direction of groundwater flow (see Figure 2-8). Leachate migration in this situation can be mitigated by lowering the liquid level of the surface impoundment. Depending on the climate and site conditions, this may be accomplished by several means:

1. diverting incoming runoff;
2. eliminating other sources of water or waste liquids; and
3. pumping liquid out of the surface impoundment.

FIGURE 2-8

EFFECT OF LEAKING SURFACE IMPOUNDMENT ON GROUNDWATER CONDITIONS


Surface Impoundment
Leachate Migration
Legend:
Water Table before Leakage
Water Table after Leakage
Direction of Flow

After a leaking surface impoundment lying above the water table has been dewatered, it can then be treated by the above-the-water-table approaches.

If the base of the leaking surface impoundment is at, near, or below the water table level, it may not be practical to dewater (drain) it, as groundwater will tend to seep back in. If this is the case, then the approach will require the same technologies appropriate for a landfill with wastes below the water table. Water table adjustment, barriers, or plume containment are likely to be appropriate responses.

2.1.1.3 Deep Mine Disposal

Mines have occasionally been used for hazardous waste disposal.

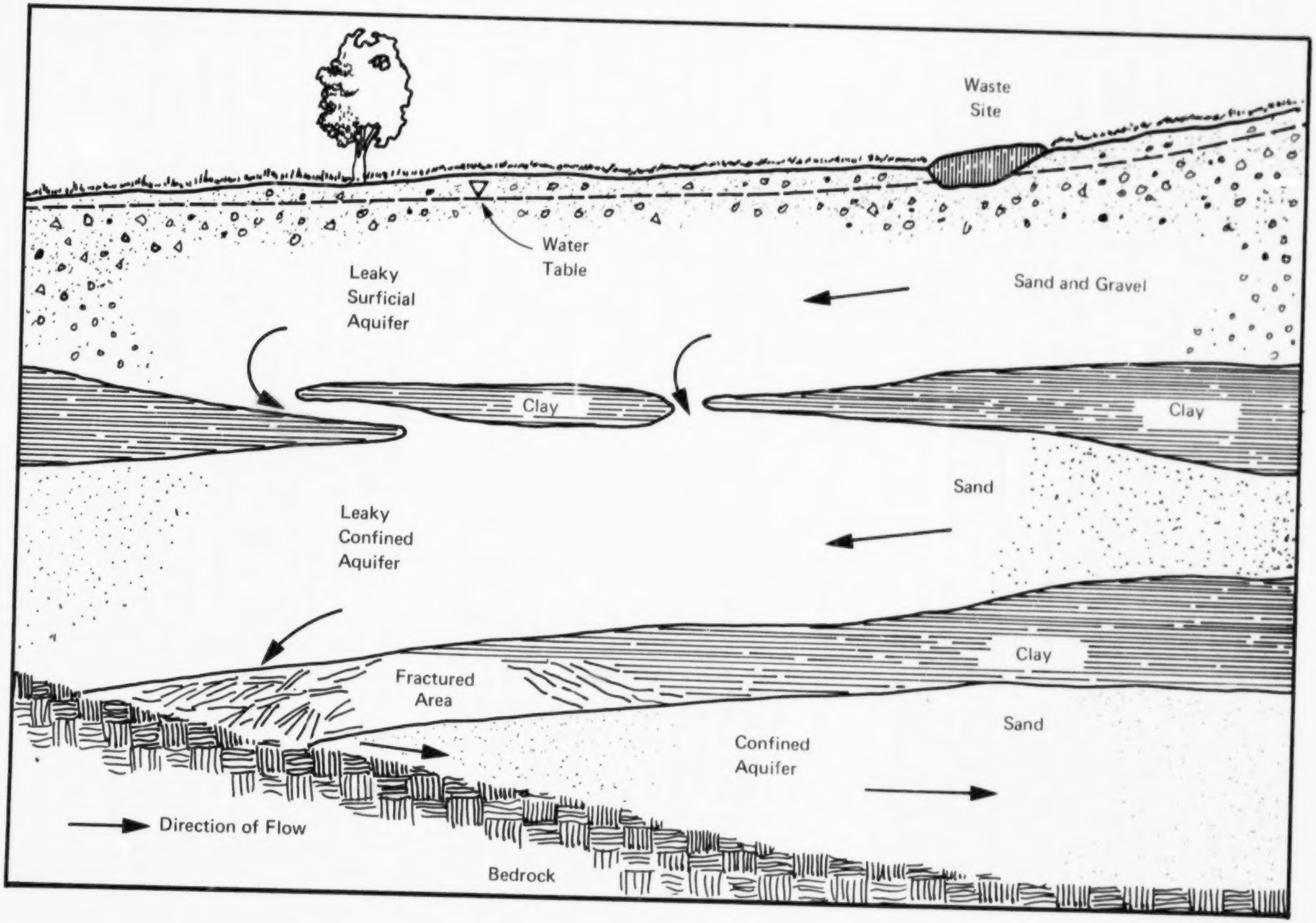
In Europe, for example, deep, dry salt mines have been used for the disposal of drummed waste. Such mines can be ideal for disposal of hazardous waste since, given proper conditions, they isolate the wastes from potential groundwater contact. Disposal of hazardous wastes in a salt mine has been proposed at a site in Northeast Ohio. However, at most mine disposal sites in the United States, effects of mine disposal on groundwater quality are complex, due to the complicated patterns of water movement through subsurface mines. Groundwater migrates to the mine walls and then may flow rapidly through the mine caverns, perhaps subsequently surfacing via seeps or tunnels, or re-entering the groundwater system. Groundwater barriers may be effective in such an environment, but should not be instituted without an intensive hydrogeologic and contamination survey to determine the proper location. Plume containment and water table adjustment techniques may also be implemented and may be more cost-effective since they do not require such extensive preliminary investigation.

2.1.1.4 General Site-Specific Considerations

Groundwater contamination problems at hazardous waste disposal sites may require different types of remedial actions as a result of other site-specific features besides the waste disposition. The most appropriate groundwater control program must account for differences in geology and the present state of groundwater contamination of the site. A common situation is one in which only a shallow (upper 8-16 meters, or 25-50 feet) unconfined aquifer is affected by hazardous waste leachate. This situation lends itself to essentially the full suite of remedial technologies, although some specific techniques, such as grouting, are effective under a limited range of soil conditions. If, on the other hand, the contaminated aquifer is artesian (confined), water table adjustment would not usually be appropriate.

Many sites exhibit a layered sequence of horizontal aquifers, separated by relatively impermeable horizontal layers of varying thickness. These layered aquifers are often weakly coupled--in other words, each aquifer is a separate entity with different flow rates, water quality, permeability, etc.; but with some water transfer between aquifers at local discontinuities of the intervening layers (see Figure 2-9). Such conditions are often described as "leaky" aquifers. Significant modification of the water balance, permeability, or head in one aquifer as a result of some remedial action, may affect the "leakage" rates among aquifers. Remedial actions may be specifically designed to effectuate such change in inter-aquifer water movement.

FIGURE 2-9
LAYERED AQUIFER SYSTEM


Waste
Site
Water
Table
Leaky
Surficial
Aquifer
Sand and Gravel
Clay
Clay
Sand
Leaky
Confined
Aquifer
Clay
Fractured
Area
Sand
Confined
Aquifer
Direction of Flow
Bedrock

Many remedial techniques for groundwater control are not feasible in deep aquifers. Although slurry trench cutoff wall construction techniques are reported to be capable of placing barriers up to 125 meters (400 feet) below the surface (Millet and Perez, 1981), 25 meters (80 feet) represents a practical limit at most sites (D'Appolonia, 1980). Sheet steel barriers cannot be installed deeper than about 30 meters (98 feet) (EPA, 1978).

Several of the grouting techniques are effective at great depth. Subsurface drainage systems are designed for shallow installation, by excavation or horizontal tunneling. Fortunately, groundwater contamination by hazardous waste disposal is often, but not always, limited to near surface aquifers. Contamination of deep aquifers can usually be "cleaned-up" only by pumping to extract contamination. However, further contamination of a deep aquifer can be reduced by measures designed to reverse or reduce the flow through confining beds or through discontinuities (cracks, voids, pipes, poorly sealed wells or bore holes, fractured rock, etc.) in the confining beds. Appropriate measures include grouting in the vicinity of discontinuities, or pumping to achieve a general reduction in driving head of the overlying, contaminated aquifer.

Another site-specific condition which influences the choice of remedial technique is the site of the existing contaminated zone. As discussed under the landfill heading, at some sites, water table adjustment to limit further leachate generation may also provide plume containment if the contaminated zone is circumscribed by the cone of depression of extraction wells sited for water table adjustment. In other cases a plume containment well must be sited far downgradient of the disposal site to reverse the flow at the leading edge of the contaminated plume. Access to appropriate locations for such plume containment wells may not be feasible for a variety of reasons.

The cost of plume control remedial measures is usually proportional to the size of the contaminated zone. Alternatively, source control cost is proportional to the size of the waste disposal site. Thus, the selection of remedial technique may be influenced by the relative area or volume of contaminated groundwater compared to the area or volume of the waste site. This ratio tends to be larger for older sites than younger ones. For example, at older sites an upgradient barrier, or water table adjustment system that limits further leachate generation, is more likely to rate higher in cost-effectiveness relative to downgradient controls or plume containment measures, than at a younger site where the leading edge of contaminated groundwater has not progressed far from the site.

The chemical characteristics of the waste and leachate will be a significant factor in the selection of leachate controls. For example:

- sheet metal barriers should not be used if exposed to corrosive leachate;
- curtain grouts are subject to degradation by specific types of leachate; and
- it is unsafe to drill through highly volatile or explosive wastes.

2.1.2 Treatment Technologies

An alternative or conjunctive approach to groundwater or leachate control and containment is treatment to eliminate or mitigate the hazard-producing characteristics of the contaminated groundwater or leachate. The original source of hazards, the waste or contaminated soil in and around the site, could be treated; techniques for this approach are discussed in a later section. Alternatively, the contaminated groundwater or leachate could be brought to the surface and treated to decontaminate and/or concentrate the hazardous components. In situ treatment is also possible and is discussed in the subsection on contaminated soils and waste materials. The technologies described in this subsection are applicable to contaminated fluid extracted or pumped to the surface. Applicable treatment technologies can be grouped into the following categories:

- biological;
- chemical; and
- physical.

Biological treatment processes are applicable to a wide range of organic compounds; chemical and physical methods are generally applicable to both inorganic and organic compounds. Generally, treatment processes produce an aqueous effluent in which the levels of hazardous constituents have been significantly reduced and a sludge or liquid residual in which the hazardous materials or process by-products are concentrated.The aqueous effluent may then be discharged to surface water, groundwater, or a municipal sewage treatment plant. Acceptable water quality standards; i.e., BOD, pH, priority pollutant levels, for the effluent will be dependent on the receiving stream and determined on a case-by-case basis. Treatment process residuals are generally hazardous materials and should be disposed or treated as such.

To select a treatment process, contaminated groundwater or leachate must be characterized and appropriate technologies tested on the laboratory scale. Contaminated groundwater or leachate from uncontrolled sites typically contains a complex mixture of many contaminants, all of which usually cannot be successfully treated by any one technology. Therefore, several technologies are generally employed. The selection of the technologies and the order of application, usually called the process train, are the key factors for cost-effective treatment (TRD 5). The most practical technologies in each treatment category and selection of a process train are discussed in the following subsections. A more extensive list of treatment technologies is discussed in detail in Section 3.

2.1.2.1 Biological Treatment

Biological treatment processes are applicable to a large number of organic wastes. Activated sludge processes are probably the most applicable to groundwater or leachate treatment. This process involves the oxidation or hydrolysis of organic compounds in an aerated reaction tank by a biomass acclimated to the influent waste stream. The treated waste stream passes through a clarifier where the activated sludge settles. A portion of the sludge is recycled to the aeration tank and the remainder removed for disposal. The effluent from the clarifier is discharged. The micro-organisms in the activated sludge can acclimate to a wide variety of waste streams. Specific micro-organisms can be isolated and utilized to seed sludges for the destruction of organic compounds. Activated sludge treatment, however, is not capable of destroying refractory compounds such as PCBs and polynuclear aromatic compounds. Some organic species and metals are toxic to activated sludge bacteria and must be removed prior to treatment. Volatile organics present in the influent may be stripped from the aqueous phase by aeration, producing undesired atmospheric emissions.

Other biological processes which may be applicable include:

- aerated surface impoundments;
- land treatment;
- anaerobic digestion; and

- trickling filters.

Aerated lagoons are similar to, but simpler than, activated sludge operation. No sludge is recycled resulting in reduced biomass acclimation and lower treatment efficiency. However, if leachate residence time in an aerated lagoon is of similar order to the sludge residence time in an activated sludge system, similar treatment efficiencies are expected. Land treatment is the application of contaminated groundwater or leachate to soils where aerobic degradation occurs as the fluid contacts soils containing natural or seeded bacteria. Often treatment includes a recycling system to collect the percolated fluid and reapply it to the surface soil.

Anaerobic digestion is the microbial degradation of organic compounds in a reactor in the absence of air. It is used primarily to treat carbohydrates, lipids, protein, alcohols and organic acids (ADL, 1977). It is inhibited by oils, fats, greases, and soluble metals. Trickling filters are structures containing an open support medium covered with a coating of microbial slime. The biologically-active coating reacts with the organic compounds in the contaminated groundwater or leachate which trickles down through the structure.

2.1.2.2 Chemical Treatment

Chemical precipitation is a conventional process for removing soluble metals from contaminated groundwater or leachate. Chemicals are added to form insoluble forms of the unwanted species. Often only the pH is adjusted to form insoluble metal hydroxides and carbonates. In cases where metal concentrations lower than can be obtained by precipitation of the hydroxides must be achieved, a sulfide chemical; i.e., sodium sulfide, is added to form insoluble metal sulfides. The insoluble metal salts are separated from the aqueous phase by gravitational settling. To promote settling, flocculating agents which act to conglomerate smaller insoluble particles into larger ones are added.

Some contaminants such as cyanide, ammonia, amines, etc., reduce the effectiveness of chemical precipitation by forming stable, soluble metal complexes. If these interfering contaminants are present, pretreatment to destroy or remove the complexing agent may be necessary.

Chemical oxidation and reduction are methods which alter the valence state of a waste constituent. Two primary applications are the oxidation of cyanide to carbon dioxide and nitrogen; and reduction of hexavalent chromium to the less-toxic trivalent form. Organics such as phenols, alcohols, and pesticides can also be oxidized. Ozone, hydrogen peroxide and chlorine are the major oxidizing agents used to treat waste. Chlorine can react with ammonia, amines, and many organics to form chlorinated reaction products which may, in themselves, be hazardous. Chlorine should be used only when tests prove its safety. In contrast to chlorine, ozone and hydrogen peroxide do not react with wastes to form any generic classes of hazardous compounds and can be used broadly. These latter two oxidants are often used in conjunction with biological and/or carbon adsorption processes to treat a diverse range of organic wastes. Ozonation coupled with ultraviolet irradiation has demonstrated potential as a primary treatment process for organics.

Ion exchange is a method to remove inorganic salts from an aqueous solution by typically exchanging a hydrogen ion for a cation or a hydroxide group for an anion. The method is expensive compared to chemical precipitation and usually employed only as a polishing step; i.e., to remove very small quantities of contaminants remaining after the principal treatment step.

Chemical neutralization is the adjustment of pH by adding a chemical agent, such as lime or sulfuric acid, to raise or lower the pH respectively. For discharge to a municipal sewage treatment plant a pH range of 6.0 to 9.5 is generally considered acceptable.

Wet air oxidation process involves the mixing of air and aqueous waste at high temperature and pressure to oxidize the waste. The method is capable of oxidizing refractory organics and should be considered for contaminated groundwater or leachate with concentrations of organics too high for biological treatment or too dilute for cost-effective incineration. Potential applications include oxidation of concentrated streams generated by other treatment methods such as reverse osmosis and ultrafiltration.

2.1.2.3 Physical Treatment

Activated carbon adsorption primarily removes organic contaminants from an aqueous waste stream. The contaminants are bound to the carbon by physical and/or chemical forces. Activated carbon is available in two forms, powdered and granular. The granular form is the most commonly used. Granular carbon can be thermally regenerated; the contaminants are generally destroyed in the process. Powdered carbon is less expensive but not easily regenerated and may be difficult to separate out of the waste stream.

Carbon adsorption is well suited for contaminated groundwater or leachate treatment because it is capable of removing complex mixtures of organic contaminants including refractory organics from aqueous waste. The process can be utilized for complete treatment for organic contamination or in conjunction with biological processes to remove refractory organics or organic constituents toxic to the biological process.

Resin adsorption is similar to activated carbon adsorption. The process is applicable to a wide range of organic contaminants. However, the high cost of resin makes the process economically uncompetitive with activated carbon adsorption except for low volume, specialized applications.

Density separation involves either the sedimentation of settleable material or the flotation of solids and/or light hydrocarbons to the surface of a liquid phase. Sedimentation is a well understood, low-cost process that typically follows chemical precipitation and activated sludge biological treatment. Flotation processes typically introduce air bubbles into an aqueous system which attach to the solid phase. The unwanted solids are then collected as they rise to the surface. The process is well suited for waste streams with high loads of grease.

Filtration processes remove suspended solids from a solution by forcing the liqid phase through a porous media and retaining the solid phase within or on the surface of the filter medium. Filter media include sand, diatomaceous earth, filter cloths and filter screens. Filtering processes are generally pre- or post-treatment steps to remove solids which interfere with a treatment process or to reduce suspended solid loads of an effluent after chemical precipitation and sedimentation. The processes are well understood and usually low in cost.

Reverse osmosis concentrates inorganic salts and some organic species; (i.e., species with molecular weights greater than 300 grams/mole), by applying pressure to force the solvent phase through a membrane which is impermeable to the inorganic salt and some organic constituents. Reverse osmosis operating efficiency is very sensitive to feed stream composition, limiting applications generally to post-treatment of effluent or a pretreatment concentration step for wet air oxidation.

Air and steam stripping are the two major stripping technologies. Air stripping involves the introduction of airflow through an aqueous system to facilitate the release of volatile constituents.

Air stripping is primarily utilized to remove ammonia from wastewaters. Steam stripping is essentially a distillation of volatile organic compounds. Air pollution problems must be considered if these technologies are applied.

2.1.2.4 Process Train Selection

To remove complex mixtures of contaminants from leachate or groundwater adequately it is usually necessary to apply several treatment technologies Applicable technologies for treating generic classes of leachate contaminants are listed in Table 2-1. This list includes technologies considered best suited for leachate treatment, in general, and is not intended to be a comprehensive list. The selection of appropriate technologies and application sequences is a key factor to accomplish cost-effective treatment. Contaminated groundwater or leachate samples must be characterized to determine what treatment is necessary and which unit processes are applicable. Treatment schemes should be tested on a laboratory and/or pilot scale prior to field implementation. Based on test results, an effective treatment process train can be designed.

2.2 SURFACE WATER

Water is the primary means by which hazardous materials can be transported from an uncontrolled disposal site to the surrounding environment. Pollutants can either be dissolved or suspended in water and carried to groundwater, surface waters, or off-site land surfaces. Water control and treatment is therefore of primary importance in remedial action at uncontrolled hazardous waste sites (TRD 8). Groundwater control, containment and collection technologies, as discussed in the previous section, are designed to prevent leachate from contaminating groundwater, and, if unavoidable or having occurred, to prevent the contaminated groundwater from contaminating aquifers and surface supplies downgradient from the waste site. Similarly, surface water control, containment and collection technologies are designed to prevent surface waters from becoming contaminated through contact with waste or contaminated soils and, if that occurs, to prevent further contamination offsite (TRD 9). Surface water technologies fall into three major categories:

1. water exclusion measures that are designed to prevent the infiltration of water to the wastes, thereby minimizing the production of leachate;

TABLE 2-1
APPLICABILITY OF UNIT PROCESSES TO LEACHATE
OR GROUNDWATER CONTAMINANTS

Waste Type	Acids, Bases, Inorganics	Metals
Applicable Processes	• Neutralization • Chemical Oxidation • Chemical Reduction • Stripping • Ion Exchange • Reverse Osmosis	• Chemical Precipitation • Ion Exchange • Reverse Osmosis
Waste Type	**Organics**	**Suspended Solids**
Applicable Processes	• Biological Treatment • Carbon Adsorption • Resin Adsorption • Chemical Oxidation • Stripping • Reverse Osmosis	• Sedimentation • Flotation • Filtration

Source: TRD 5

2. water collection measures that are designed to prevent surface water containing hazardous waste leachate from contaminating off-site soil and water resources; and

3. erosion control measures.

The next sub-section discusses the important general characteristics of sites that determine the applicability and design of these measures. Discussion of technical approaches follows that discussion.

2.2.1 General Characteristics

Water collection and exclusion technologies should be designed to handle the maximum quantities of water expected (from preliminary analysis) with a margin of safety. This is especially true of a water collection system since its failure would mean the release of potentially hazardous leachate. Maximum quantities of runoff can be expected during and after an intense storm, depending on the hydrologic conditions of the site. In mountainous areas spring thaw can cause a peak runoff due to rain and snowmelt. Coastal and riverine flooding can also be a problem in certain areas. The hydrologic analysis should indicate the maximum flow of water which can be expected. Surface water controls should be designed to at least withstand a 24-hour, 25-year rainfall (TRD 8). More stringent design may be necessary in certain areas where flooding is considered likely or where site hazards are considered particularly acute.

2.2.1.1 Water Exclusion Measures

Water exclusion measures are designed to prevent water from getting in contact with the waste. This can be done in two ways:

- prevent runon from off-site sources; and
- prevent infiltration through the site surface.

Runon can be defined as any water originating off-site which flows across the surface of an uncontrolled hazardous waste site. It includes stormwater, floodwater and snowmelt. Diverting this water around or away from the waste site greatly reduces the quantity of water flowing across a waste site and therefore reduces the potential for infiltration and contamination of off-site areas via contaminated runoff. If all water from off site is successfully diverted around or away from the site, then the only manner in which water can reach the site surface is through direct precipitation or groundwater discharge.

Control methods function by modifying the water balance at a site. Proper control can minimize the production of leachate and limit the flow of leachate to the surface water collection system. The water balance for surface water can be modeled by the following equation:

$$P - E - T = R + I + \Delta S$$

Where:

P = direct precipitation
E = evaporation
T = transpiration
R = runoff
I = infiltration
ΔS = change in storage

It is important to understand which of these terms are most important at a given site. This will depend on site-specific and regional characteristics as well as the nature of the precipitation event. Site investigation should include a hydrologic study to analyze the effect of these factors on the terms in the water balance. TRD 2 describes the water balance in detail and provides an interactive, user-friendly computer program for quantifying the water balance parameters at a solid waste disposal site.

For precipitation falling on site, the objective of water exclusion measures is to prevent leachate generation by eliminating infiltration. Since precipitation cannot be controlled at a site, the water balance shows that this must be accomplished by increasing the other terms in the equation. On-site water exclusion measures are therefore designed to maximize the quantities of water that run off or are otherwise transferred off site. Some methods are also designed to increase potential surface storage by accelerating the removal of water through evaporation and transpiration.

2.2.1.2 Water Collection and Transfer Measures

Surface water collection measures are designed to prevent surface water leachate from contaminating off-site areas. They are used in conjunction with water exclusion measures. Water exclusion measures are primarily concerned with the quantity of water that infiltrates at the site. Water collection measures, on the other hand, are concerned with the quantity and quality of water moving off site. Five options exist for dealing with water that has run off or is transferred off-site (TRD 5):

1. route uncontaminated flow, from on-site or off-site diversions, directly to surface water courses or to a holding or storage pond for more controlled discharges;

2. route mildly contaminated flow to holding or storage area and treat prior to discharge;

3. route contaminated runoff to on-site leachate treatment plant;

4. place contaminated runoff back into the disposal area; and

5. ship contaminated runoff off site for appropriate treatment and disposal.

Runoff quality is a function of waste characteristics (for example, solubility, pH, percent liquid), and the type of interaction occurring between water and waste (for example, time of contact, mixing, scouring).

2.2.1.3 Erosion Control

Surface water measures are concerned not only with the prevention of infiltration and off-site movement of contaminants, but also with erosion control. Erosion of soil can cause buried wastes to be exposed and transported with contaminated soil off site, and sediments can accumulate in storage basins, limiting their effectiveness. Erosion can also damage remedial action technologies if runoff flow velocities and volumes are not carefully controlled (TRD 11). This complicates the relationship between terms in the water balance. Technologies for increasing runoff from the site, for example, must be designed not only to maximize the amount of water running off, but also to keep overland flow velocities below the erosive limit and to prevent channelization (TRD 8).

2.2.2 Surface Water Control Technologies

There are a number of technologies which can be used for the control, containment or collection of surface water. Water exclusion measures include barriers and landscaping techniques. Water collection measures include routing and discharge technologies. These technologies, summarized in Table 2-2, are designed to perform six basic functions:

1. prevent runon;

TABLE 2-2
SURFACE WATER TECHNOLOGIES

	Primary Function					
Technology	Minimize Runon	Minimize Infiltration	Reduce Erosion	Protection from Flooding	Collect and Transfer Water	Discharge Water
Flood control dikes				X		
Runoff control dikes	X		X			
Terraces	X		X			
Channels			X		X	
Chutes			X		X	
Downpipes			X		X	
Grading	X		X			
Surface seals		X				
Vegetation	X	X	X			
Seepage basins						X
Seepage ditches						X

2. control infiltration;
3. prevent erosion;
4. collect and transfer water;
5. store and discharge water; and
6. protect against flooding.

Some technologies perform more than one of these functions. Other technologies may require backup or complementary technologies or may only have limited application at a given site. A surface water management system, therefore, may require a combination of technologies to minimize the production of leachate and prevent off-site contamination adequately.

2.2.2.1 Prevention of Runon

Technologies which are designed to prevent or reduce runon include: dikes, diversion channels, floodwalls, terraces, grading and revegetation. Temporary diversion dikes, diversion channels and terraces are diversion measures constructed upslope of a site to direct runon from off site to a collection system or away from the site. Terraces are used in combination with dikes or ditches to channel water stopped by the terraces away from the site. Flood control dikes (or embankments) and floodwalls are flood protection measures constructed as perimeter structures surrounding a waste site to isolate the site from floodwaters. Embankments in areas subject to river flooding are called levees. They are more expensive than runoff dikes or terraces and will usually be used only in areas where flooding is likely to be a problem. Floodwalls, which are more expensive than levees, can be used at sites with insufficient land area to construct a levee. Grading and revegetation, which are primarily for erosion control, reduce quantities of water available for runon by increasing off-site infiltration and interception. They are used in conjunction with the other technologies mentioned above to increase their effectiveness.

2.2.2.2 Prevention of Infiltration

The primary method for preventing the infiltration of on-site surface water is surface sealing. This involves placing a cap or cover of low permeability over portions of the site where infiltration needs to be eliminated. Surface seals should be graded so that the maximum amount of water will run off without causing significant erosion. Revegetation of the cover will reduce erosion but might also increase infiltration. The roots of the vegetation provide a pathway for infiltration through the surface layers and may penetrate the barrier layer. However, with proper selection and management of the vegetation cover, much of the infiltrating water can be taken up by the root system. This amount will depend on the quantity of precipitation and runoff, as well as other climatic conditions. A surface seal must therefore be carefully designed to satisfactorily reduce infiltration and maintain stability throughout the desired lifetime.

2.2.2.3 Erosion Control

Erosion can be modeled by the Universal Soil Loss Equation (TRD 1). The equation is:

$$A = RKLSCP$$

Where:

A = average soil loss, in tons/acre/year

R = rainfall and runoff erosivity index

K = soil erodibility factor

L = slope length factor

S = slope steepness factor

C = cover/management factor

P = practice factor

Erosion potential is, therefore, a function of the inherent erodibility of the soil (K) as well as many other factors. The soil erodibility factor can be determined using a nomograph and depends on soil structure, texture, and permeability. Soil erodibility is also often expressed in qualitative terms (high, moderate, low or erosive, resistant). Methods for determining values for the factors in the equation can be found in TRD 8.

Surface water control technologies reduce erosion by reducing slope length (L), slope steepness (S), or improving soil management (C). Dikes, diversion channels, and terraces can be used to reduce slope length. Dikes used for this purpose are called interceptor dikes. They differ from diversion dikes primarily in their design specifications. Slope steepness is reduced by grading. Proper grading allows water to run off without forming channels or attaining sufficient velocity to cause significant erosion. Choice of vegetation is crucial and will depend on soil fertility, climate, hydrologic condition, and desired function. Revegetation should be considered in increasing the stability of all earthen surface water control measures.

2.2.2.4 Collection and Transfer of Water

Collection and transfer technologies include waterways, chutes and downpipes. They serve to collect water which has been diverted away from the site or prevented from infiltrating, and transfer it either to direct discharge or storage for treatment or more controlled discharge. Chutes (or flumes) and downpipes (or drainpipes) are designed to transfer water away from diversion structures such as dikes or terraces to stabilized channels or outlets. Waterways can be used to intercept or divert water as well as collect and transfer water diverted elsewhere. They are the stabilized channels that form the base of the surface water collection system. They collect water from diversion structures, chutes, downpipes and ditches and channel it either to treatment or discharge.

2.2.2.5 Storage and Discharge of Water

Water storage and discharge technologies include seepage basins and ditches, sedimentation basins, and storage ponds. Their function will depend on the level of contamination of the water they receive. Seepage basins and ditches are used to discharge uncontaminated or treated water downgradient of the site. Sedimentation basins are used to control suspended solid particles in surface water flow. They can be part of the water treatment process and their design will depend on that process and the amount of solids in the surface water. Finally, storage ponds are used to store collected surface and groundwater when flow rates are in excess of treatment or discharge capacities. Sedimentation basins and storage ponds are not discussed in Section 3. Further information can be found in Erosion and Sediment Control (EPA, 1976, Vol. I and II).

2.3 CONTAMINATED SOIL AND WASTE MATERIALS

Waste materials and contaminated soil are the basic source of problems at uncontrolled sites. Surface waters may become contaminated with run off that has contacted waste and/or contaminated soils, and groundwater may be threatened by leachate from or direct contact with the waste and contaminated soil. Air emissions result from the volatilization of waste materials or entrainment of waste and/or contaminated soils. Containment measures such as slurry walls, covers, leachate collection systems, etc., can effectively isolate waste, but may require long-term care. Failure of containment systems may result in renewal of the original environmental hazards at the site and surrounding area. In contrast, removal or on-site detoxification of waste and contaminated soils offer a long-term solution and may render the site suitable for alternative uses. Removal of all contamination, however, may be very costly and application of on-site detoxification methods may be limited by the complexity of wastes in uncontrolled sites.

Waste materials include:

- landfilled sludges, solids and drummed materials;
- surface impoundment liquids and sludge bottoms;
- drummed waste stored above ground; and
- land treatment soil layers.

Soils become contaminated by seepage from or mixing with wastes or leachate from waste. Therefore, soil contamination may extend beyond the area of waste disposal activities.

Landfilled waste and soils may be mobilized by water percolating through the site, surface runoff, volatilization, and air entrainment of particulates. Drummed materials disposed of in landfills present a special set of problems. Incompatible waste isolated by containment in drums may be disposed of side by side in a landfill. If the drums corrode and leak, the waste could mix and react violently. An uncontrolled landfill site in Coventry, Rhode Island was recognized when drums containing water-sensitive materials corroded and were exposed to water resulting in explosions. Such occurrences endanger the safety of personnel present at the site and could possibly damage other remedial containment measures resulting in costly repair actions.

Typically, stored waste is contained in 55-gallon drums which can corrode and leak. Potential problems include:

- soil contamination;

- other waste contamination;
- surface water contamination;
- groundwater contamination;
- air emissions/odors; and
- fire.

If large quantities of reactive and flammable waste are present, a fire could generate a plume of toxic gases, potentially dangerous to the population downwind. Analyses of smoke from the April 21, 1981 fire at the Chemical Control Corporation in Elizabeth, New Jersey indicated the presence of benzene at a level of 10,000 ppm (Finkel and Golob, 1981) a level 1,000 times the OSHA eight-hour time-weighted average concentration standard for benzene. Other problems that could be caused by fire are contamination of large volumes of debris and soil on site, and of the water used to control the fire.

Major factors affecting the choice of removal versus containment or combination of options are:

- transport distance to treatment and disposal facilities;
- quantity of waste and soils;
- need to implement other remedial actions independent of removal;
- nature of hazard posed by the abandoned site;
- treatability of wastes and soils; and
- cost.

The technologies applicable to removal and detoxification technologies are discussed in general terms below. Each of the technologies is discussed in more detail in Section 3.

Four types of response actions to waste and contaminated soils are:

- removal;

- on-site treatment;
- in situ treatment; and
- on-site secure disposal.

Removal methods transfer the wastes to off-site treatment and/or disposal facilities. On-site treatment decontaminates the wastes and soils at a facility located on or adjacent to the site. In situ treatment methods decontaminate the wastes in place. On-site secure disposal involves, in effect, building a secure landfill on part of the site for the contaminated materials. It may involve rearranging the wastes to clear an area for reconstruction. This approach will not be discussed further in this report. For further information on controlled disposal facilities, please refer directly to the TRDs. The eleven currently available TRDs are summarized in Section 1. In particular TRD 1 discusses covers, TRD 4 discusses liners,and TRD 8 discusses closure and post-closure planning.

A combination of these approaches may be applied at a site. For instance, a sludge could be excavated, dewatered on site, and the residual transported to a secure landfill. An overview of technologies applicable to each approach is presented below.

2.3.1 Removal

Excavation of landfilled waste is the major removal technology. Either a backhoe or a dragline crane is commonly employed. Backhoes are available to reach depths up to 21 meters (70 feet)(ASCE, 1982). Draglines are available to reach depths of nearly 18 meters (60 feet)(EPA, 1982). The backhoe is usually the more versatile piece of equipment in that it is more maneuverable, and can be conveniently used to backfill the excavation (Grim and Hill, 1974). Although excavation at construction sites is a well-demonstrated technology, the application to hazardous waste sites presents some unique problems. The load-bearing capacity and fill density which may be affected by the buried waste should be considered before deciding to operate heavy equipment at the site. Landfilled drums must be handled with caution. If drums are punctured or already leaking, additional soil at the site can be contaminated. Sparks created by drum contact with grappling hooks can ignite flammable or explosive waste. Typically, drums are moved to a staging area for transfer or to a secure drum or a tank truck.

Operations at a site may be hazardous and special precautions should be taken. Operators of equipment may be exposed to hazardous vapors and to direct contact with liquids, solids, and contaminated surfaces. Protective clothing, including respirators may be required in some cases. Equipment may become contaminated and require decontamination before it can be taken off site and used somewhere else. Dust raised by activities at the site may be contaminated with hazardous materials and should be minimized through application of proper dust suppression techniques.

Surface impoundment sludge bottoms and contaminated soils can be removed by dredging techniques such as centrifugal pumping and hydraulic pipeline dredges. Both methods are readily available and comparable in cost. The waste can be pumped directly to tank trucks as a low-solid content sludge (less than 20 percent solids). If transport distances to a dewatering facility are large, it may be cost-effective to dewater on site. Impoundments can be drained prior to sludge removal by pumping the liquid phase to a tank or other receptor. The uncovered sludge could present an odor problem. Dried sludges can be removed with the backhoe or dragline equipment discussed previously.

Several approaches are available for handling drummed wastes. Drums in good condition can simply be loaded onto a truck and transported to an off-site treatment, storage, or disposal (TSD) facility. The contents of corroded drums can be transferred to secure drums or mixed with a solidification material such as kiln dust, for off-site disposal. A third alternative is to blend the contents of drummed waste in holding tanks and subsequently pump the blended materials into a tank truck for removal. Blending operations must be carefully monitored; extensive preblending and sampling of drums is necessary to screen for incompatible waste.

2.3.2 On-site Treatment

Approaches to on-site treatment of soils and waste include:

- physical/chemical/biological treatment;
- solidification/ stabilization; and
- incineration.

Physical/chemical/biological treatment methods either detoxify a waste or separate and/or concentrate a waste.

Solidification/stabilization technologies incorporate waste in a solid form that reduces leachate generation potential and renders the waste more suitable for landfilling or long-term storage. Incineration thermally decomposes organic hydrocarbons waste principally to carbon dioxide and water. Other gaseous species and a solid residue may also be produced depending on the waste composition. Inorganic constituents, after incineration, yield solid oxides and acids predominantly.

2.3.2.1 Physical/Chemical/Biological Treatment

There are many individual unit processes for physical/chemical/biological treatment of waste materials and contaminated soil, including, for example, the following twenty processes (TRD 5):

- biological treatment
- carbon adsorption
- catalysis
- chemical oxidation
- chemical reduction
- chemical precipitation
- crystallization
- density separation
- dialysis/electrodialysis
- distillation
- evaporation
- filtration
- floculation
- ion exchange
- resin adsorption
- reverse osmosis
- solvent extraction
- stripping
- ultrafiltration
- wet oxidation

Each unit process is applicable to only certain waste streams. For example, carbon adsorption is a good method for removing chlorinated organics, but not metals, from an aqueous solution. A more detailed discussion of the applicability of each technology will be presented in the next section.

A single unit process may be applicable to homogeneous drummed waste at a site or a surface impoundment which has received a homogenous waste stream. However, wastes at abandoned sites are typically complex mixtures. Impoundments and barrels may contain wastes from several process streams and drummed waste from numerous sources can cover a wide spectrum of waste types. One component of a waste may interfere with the treatment of another by a single unit process. It is usually necessary to combine several of the above unit processes to treat waste mixtures. The process sequence is dependent on the technology used for each treatment category. For example, the process sequence for treating an aqueous mixture of metal salts and chlorinated solvents could be either of the two shown in Figure 2-10. To select the proper unit process(es) and treatment sequence, extensive lab testing should be conducted. An extensive discussion of treatment train selection can be found in TRD 5.

2.3.2.2 Solidification/Stabilization

Solidification/stabilization technologies include (TRD 6):

- cementation, using Portland cement;
- pozzolanic cementation;
- thermoplastic binding;
- organic polymer binding;
- surface encapsulation; and
- glassification.

These technologies are applicable, in general, to diverse types of inorganic waste materials, but not, in most cases, where greater than 10 to 20 percent organic materials are present. Important waste characteristics that impact solidification/stabilization technologies include: pH, buffer capacity, water content, and specific inorganic constituents (TRD 6).

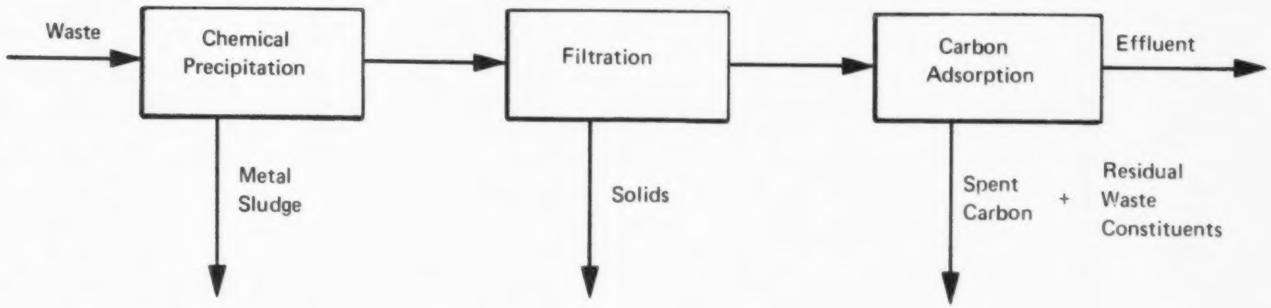
Of the methods listed, cementation and pozzolanic reactions are generally the most widely applicable to wastes over a wide range of composition. In the two cementation techniques, Portland cement or lime and a pozzolanic material; i.e., fly ash or cement kiln dust, respectively, are mixed with a slurry of the waste stream. After the slurried mix has set up, the volume is typically twice the initial waste volume. The cemented product has permeability on the order of $10^{-5}$to 10^{-7}cm/sec., high structural integrity, and improved resistance to leaching. Inorganic constituents in the waste, however, may cause large changes in the physical and chemical properties of the cemented product.

Thermoplastic binding (for example, with asphaltic bitumens) is suitable for inorganic waste with little or no organic materials

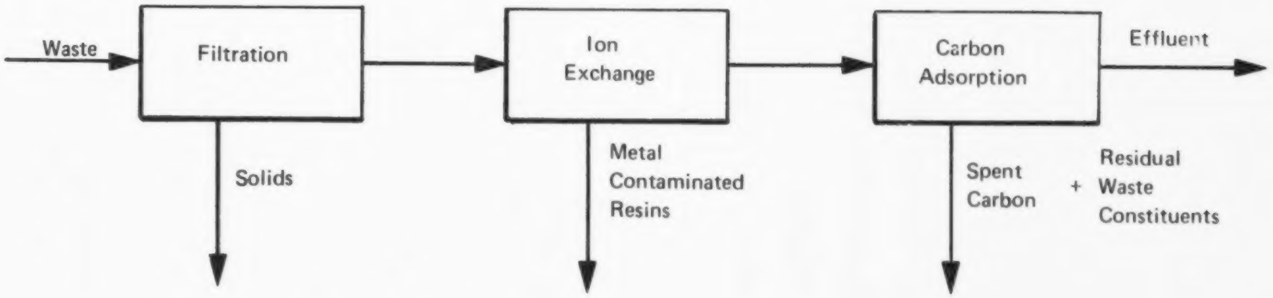
FIGURE 2-10

ALTERNATIVE TREATMENT SEQUENCES FOR AN AQUEOUS MIXTURE OF METALS AND CHLORINATED DEGREASING SOLVENTS

Alternative #1


Waste
Chemical Precipitation
Metal Sludge
Filtration
Solids
Carbon Adsorption
Effluent
Spent Carbon
+
Residual Waste Constituents

Alternative #2


Waste
Filtration
Solids
Ion Exchange
Metal Contaminated Resins
Carbon Adsorption
Effluent
Spent Carbon
+
Residual Waste Constituents

present. Thermoplastic binding is more expensive than cementation. The thermoplastics are sensitive to attack by many organic constituents.

Encapsulation is a related technique in which waste in containers or waste bound up in a cement, polymer, or thermoplastic matrix is enclosed in a stable, water resistant covering. This method, now in the developmental stage, may be very useful in relocating drummed wastes at the inactive site.

2.3.2.3 Incineration

Incineration is a proven organic waste destruction technology. An extensive discussion of incinerator technology and its relevance to waste treatment can be found in the "Engineering Handbook for Hazardous Waste Incinerators" (EPA, 1981). A rotary kiln incinerator will be, generally, the best form of equipment for mixed wastes containing solid residues found at abandoned or uncontrolled sites. Incineration is often more expensive than other treatment technologies, but offers effective destruction of organic waste including refractory compounds, such as PCBs. The incinerator should include a pollution control device, such as a scrubber, where emissions are likely to cause an air pollution problem (e.g., with acidic emissions). The wastes can be incinerated on site or off site at an existing facility. On-site incineration may be the preferable treatment method for highly toxic, organic waste, particularly if there are large volumes of contaminated waste that are expensive to transport. Mobile incinerator systems have been marketed by commercial firms. One such system uses molten iron or molten salt in its primary chamber and is reported to achieve 99.9999 percent destruction efficiency for PCB materials (Chemical Engineering, 1981). Incineration of explosive compounds, while not currently proven, may be possible in the near future.

2.3.3 In Situ Methods

In situ methods treat the wastes in place and are similar to the on-site treatment techniques discussed above, except that the wastes are left in place and the process takes place within the waste mass. Application of in situ methods could eliminate or reduce the need for expensive excavations or decontaminated actions. Potential technologies include:

- biological;

- physical/chemical detoxification;
- vitrification; and
- solution mining (extraction).

One biological approach is land treatment at a site containing surface soil contaminated with organic waste from leaking barrels that have been removed. Aeration of the soil together with control of surface water infiltration and runoff, will promote the activity of soil organisms and, thus, reduce the residual toxicity. Inoculation of active species can be used to promote the activity of the indigenous species. Biological treatment is limited to organic constituents; the other methods are applicable to a wider range of waste.

Physical/chemical methods introduce a reactant into the wastes to detoxify the hazardous components by chemical reaction or by adsorption on a substrate such as activated carbon. Oxidation of cyanide wastes with sodium hypochlorite has been used at an inactive cyanide salt disposal pit in the Midwest. Other variations of the class of methods include reduction of hexavalent chromium with ferrous sulfate and the precipitation of a wide range of heavy metals by pH adjustment and sulfide addition.

Generally, a waste must be fairly homogenous to apply in situ physical/chemical methods. Physical/chemical in situ methods pose the risk of generating or volatilizing other toxic constituents by action of the added reagents; it is important to characterize the wastes thoroughly before using this approach.

In in situ vitrification, the waste is fused into a glassy, stable matrix by heating it in place. One such method now under development, passes an electrical current through the wastes to produce high temperature and subsequent fusing of the wastes (TRD 6).

Solution mining, also referred to as in situ extraction, introduces a solvent liquid into the waste mass. The hazardous (and other) components in the waste are gathered up by the solvent and collected for disposal or treatment on the surface from wells placed to intercept the solvent plume. This process might be called controlled leaching as the solvent behaves in a manner essentially identical to leachate. Solvents include water, acids, and ammonia. Various agents, such as chelating compounds (ethylene diamine tetracetic acid, EDTA), may be added to increase the solubility of low-solubility substances such as heavy metals (EPA, 1982).

2.3.4 On-Site Disposal

This approach consists essentially of building a secure disposal facility on site, using permitted techniques. Such a site will have to meet federal, state and local regulations for hazardous waste treatment storage and disposal. If this approach is used, the wastes and contaminated soils may have to be moved around the site while the new disposal area is being constructed. For details on the technologies for constructing secure facilities, the entire set of TRDs should be consulted.

2.4 AIR

Historically, air contaminants (gaseous emissions or fugitive dusts) have not received as much attention as hazardous materials in the leachate, groundwater or surface water at uncontrolled disposal sites. Odors, although not usually hazardous, per se, may create a public nuisance and complicate the development of a remedial action program addressing the hazardous problems at the site. Gaseous emissions and fugitive dusts may be hazardous, i.e., toxic, corrosive, reactive, or ignitable. Continued generation of gases under a surficial cover or cap could lead to cracking or perforation of the cover if pressure build-up is allowed to exceed the covering material's working limits. These direct and indirect problems require careful assessment during site investigations and have a characteristic set of remedial technologies quite different from those applicable to leachate, groundwater or surface water contamination.

2.4.1 Gaseous Emissions

2.4.1.1 Source of Emissions

Gases may be emitted at a waste site by the vaporization of liquids, venting of contained or entrained gases, or by chemical or biological reactions with the solid and liquid waste materials. Various organic compounds may slowly but continuously volatilize from wastes at a landfill and from the exposed top surface of a surface impoundment. Low boiling-point organic materials, including contaminated solvents, if improperly contained will emit vapors that may be ignitable or toxic. Examples of such potentially hazardous emissions and their sources are given in Table 2-3 (TRD 7).

Inorganic gases can also be emitted from a waste site. Oxidizing gases such as chlorine may react with polymeric liner materials

TABLE 2-3
SOURCES OF GASEOUS EMISSIONS

Sources	Gases
Proteinaceous and cellulosic wastes	Organic decomposition gases methane hydrogen sulfide
Uranium mill tailings	Radon
Chemical process waste impoundments	Benzene Chloroform Trichloroethene Other chlorinated hydrocarbons
Industrial liquid and sludge waste (notably sugar beet, pulp, tanning and chemical process industries)	Methane Methylmercaptan Dimethyl-disulfide Hydrogen sulfide

and organic materials. Such gases are either chemical reaction products or are already present in containers or entrained in the wastes.

Waste sludges containing organic matter, whether contained in a discrete sludge layer (in a surface impoundment, for example) or deposited within the subsoil in some distributed concentration (at a land treatment facility, for example), generally undergo decomposition due to biological activity. Depending on the type of site, the biological degradation may be either aerobic or anaerobic. Under aerobic conditions, organic constituents are gradually oxidized to intermediate products (for example, organic acids and alcohols) and then converted to organic residues and gases. Under anaerobic conditions, reduced sulfur, volatile intermediate products, and methane may be vented.

The rate of waste volatilization in impoundments or landfills is dependent both on the chemical and physical properties of the waste and also on the properties of the surrounding environment.

Volatilization rate depends directly on vapor pressure which increases exponentially with temperature. Vaporization of organics from water surfaces is affected by their solubility. The rate also depends on mixing at the surface, which depends on wind speed and liquid turbulence. Increasing temperatures generally reduce the solubility and increase the emission rate into the air.

Gaseous emissions may be increased during the period when remedial action operations are being undertaken. Removal of drums may cause rupture or leakage of highly volatile or reactive materials. Excavation or grading operations may change the biological environment, causing action to shift from anaerobic to aerobic, or vice versa, producing new gaseous emissions. Activities at old surface impoundments, such as pumping, dredging or excavating residue, may lead to increased emissions due to the removal or breakup of a dried-up surface barrier or the mixing of the surface liquid layer with liquids of higher vaporization potential from subsurface regions.

Gaseous emissions at the surface are mixed into the ambient air and are transported off site by the natural dispersive properties of the atmosphere. The gaseous emissions move from subsurface regions to the surface by diffusion and bulk gas flow in the soil. If there is a barrier to the flow at the surface -- for example, a man-made cover or cap or a natural barrier -- then, unless physically constrained, gaseous emissions will move laterally through soil. For example, this mechanism has been shown to result in radon buildup in structures some distance from uranium tailings piles, and in methane explosions in structures near landfills. Gases may also be dissolved in groundwater and move in both the vertical and horizontal dimensions along with the water flow. Gas flow within the soil is dependent on free space diffusivity, porosity and the degree of water saturation. Soil gaseous porosity can vary by a factor of 2 from dense gravel to loose clay. Saturation may vary from a low of 2 or 3 percent in very dry soil, up to 100 percent.

2.4.1.2 Controlling Gaseous Emissions

Several remedial approaches can be used to treat gaseous emissions. Removal or deactivation of all sources of emission will control the problem permanently at the site. Removal may transfer the problems to another site, but one where means should be in place to handle the emissions under controlled conditions. Techniques for removal or on-site deactivation are discussed in the following sub-section.

Increasing moisture (for example, by irrigation) in surface and soil layers can both reduce the rate of gaseous emissions at the surface and enhance biological decay. Waste stabilization will reduce the rate of volatilization but some gaseous products of anaerobic decay may still permeate the waste mass and reach the surface.

Controlling emissions from surface impoundments can be effected by stripping the entrained and dissolved gases from the liquid wastes or conversely by increasing the gases' solubility by adding chemicals; or mixing to disperse the gases uniformly through the liquid layers. Emissions can be reduced by dewatering the lagoon by draining or sometimes by adding bulking agents such as soil, cement, or crushed coral.

Control of volatilization from the surface of landfills and impoundments can be accomplished by covering the site, using a temporary or permanent cover. Covers are usually placed directly onto the surface of landfills. On impoundments, covers may float directly on the surface or be supported above the surface. Soil clay, synthetic films and textiles, metals, and glass have been used for covers. Floating material covers on liquid impoundments include foams, beads, low permeability liquids, and thin plastic films. Covers can be very effective in reducing vapor emissions as shown in Table 2-4 (TRD 7). These data, based on a laboratory study of the rate of vapor losses from hexachlorobenzene (HCB), indicate that reductions of the order of 1000-fold could be obtained by using covers of soil.

If no means to control gas production within the waste mass is provided, then the gases may build up under the cover, causing cracking or may move laterally off the site to nearby structures. The general approach to control this problem is to collect the gases and vent them to the atmosphere with or without treatment, depending on the nature of the hazard. Collection systems in landfills include trenches, pipe vents, and barriers. Supported covers on impoundments may also serve as gas collection systems. Trenches are rock- or gravel-filled ditches within or around the site where the gases entering the trench will flow to a central collection point or will flow upward to the surface and be released directly to the atmosphere. Pipe vents operate similarly. Perforated pipe is laid through or around the site to intercept the permeating gases and provide a conduit to a controlled release point.

Barriers to gas movement may be used in conjunction with collection systems to channel the gas flow toward the collection points. Barriers may be made of compacted clay or impervious plastic or metal materials. Barriers can be used to prevent the lateral

TABLE 2-4
EFFECT OF DIFFERENT COVERS ON LANDFILL HCB VAPOR EMISSIONS

Cover	HCB[a] Vapor Flux (kg/hectare/year)
None	317.00
1.9 cm topsoil	4.56
0.15 mm polyethylene film	201.00
1.43 cm water	0.38
120 cm topsoil (silty clay loam)	0.066

[a] HCB = hexachlorobenzene

Source: TRD 7

flow above the water table through soil pores or cracks to nearby structures. Groundwater barriers, discussed earlier, can be used to limit the lateral transport of dissolved gases below the water table.

Collection systems may use the natural pressure and diffusive forces to drive the gases through the system or may include pumps. Often the collected gases can be vented directly to the atmosphere, using its dispersive properties to reduce their toxic or ignitable potential to an acceptable level. If direct release is not acceptable, the collected gases and vapors can be treated before venting by a variety of methods including:

- physical/chemical methods;
- thermal oxidation; and
- incineration.

Adsorption removes the hazardous components by fixation on a bed of solid sorbent, usually activated carbon. When the sorption capacity of the bed becomes exhausted, it can be regenerated by reactivation or be replaced with fresh sorbent.

Absorption dissolves the undesired components from a gas in a liquid solvent by either bubbling the gas through the liquid in packed or plated columns, or spraying the liquid through the gas stream in spray towers. Once the hazardous components are solubilized, then any of the physical/chemical processes for treating groundwater or leachate, described above, may be used for detoxification.

In thermal oxidation or incineration, the undesired volatile components are destroyed by reaction at high temperature. Thermal oxidation generally refers to systems in which the gas supports combustion on its own without auxiliary fuel. Methane emissions from landfills can be burned in flares, a common type of burner developed originally for natural gas and oil well control. Incinerators for gases are often called after burners. The high temperature necessary for thermal destruction of the hazardous components is achieved by combustion of auxiliary fuel.

2.4.2 Fugitive Emissions

Fugitive emissions are particulates that are lifted from the ground by wind and may be caused by one of the following processes:

- wind erosion of the exposed waste materials;
- re-entrainment of particulate matter by vehicular traffic on haul roads and exposed surfaces;
- excavation of waste materials during remedial action; and
- wind erosion of the cover soil.

Wind erosion will depend on the waste type, moisture content, wind velocity and surface geometry. Researchers generally agree that between about 2.5 and 10 percent of all the soil eroded due to wind becomes airborne as suspendable particulate matter (Evans, J. et al., 1979).

The amount of fugitive emissions generated by excavation activity is generally insensitive to the ambient wind speed, except at very high wind speeds as in a storm. But the wind speed does determine the drift distance of large dust particles and, therefore, the localized impact of the fugitive dust source. When remedial procedures are completed, the site will often be covered with a soil layer that may act as a source of fugitive dust if it is not properly constructed to prevent this.

Fugitive dust control techniques vary according to the type of surface encountered. Dust suppressing treatments for roadways generally include oil or calcium chloride. Excessive application of calcium chloride should be avoided, as this compound can leach into and contaminate groundwater. Care should be exercised in selecting a dust control method to be sure that it does not adversely affect the treatment process or cause environmental damage.

Wetting and stabilizing are the most commonly used techniques for preventing and/or reducing fugitive dust emissions from excavation activities. Often waste materials possess sufficient moisture so that application of soil stabilizers or wetting for dust suppression would not be required. Wet suppression, by spraying, for example, is a fairly inexpensive, short-term method of controlling dust on a confined site. Gravel added to a haul road surface acts as a physical stabilizer. Chemical stabilization uses binding materials that cause dust particles to adhere to larger surface particles. The effectiveness of this method is extremely variable, primarily depending on the amount of traffic.

Suppression of dust emission from soil covers can be accomplished by use of physical, chemical, or vegetative stabilization. Physical stabilizers cover the exposed surfaces with a material that prevents the wind from disturbing surface particles. Stabilizer materials include soil, rock, crushed or granulated slag, bark, and wood chips. The main drawback to physical covers is the high cost involved in their application. This is especially true when the cover materials are unavailable in the immediate area. Most chemical stabilizers only provide dust suppression for a short period of time, generally no more than a few months. After that, a more permanent solution (vegetative cover) is needed.

Vegetation may be used to stabilize a variety of exposed soil surfaces. Vegetation provides an effective method of control along with making the site more aesthetically acceptable. Efficiencies close to 100 percent should be achieved with complete vegetative covering on some sites. The soil must be prepared for vegetation by adding fertilizers, organic matter, pH neutralizers and the establishment of proper slope and drainage. Plants compatible with the soil type, climate, growing conditions and site end use, including the type of maintenance expected, should be chosen. The selected species must also be insensitive to gases that may permeate into their root systems from continuing chemical and biological activity in the waste mass (TRD 1, TRD 11).

2.4.3 Odor

Industrial wastes frequently have a characteristic odor of a chemical nature. The waste can develop an extremely unpleasant odor if the waste contains sufficient, easily decomposable organic matter and if oxygen is limited. Odor does not necessarily mean that environmental damage is occurring but is sometimes a serious enough problem to prevent the land treatment of waste at a site that is otherwise ideally suited for the purpose.

Odors from waste material are usually a result of the formation and release of sulfides, mercaptans, indoles, phenols, or amines, usually under anaerobic conditions. Disposal techniques should be designed to avoid their formation or release in the first place. Even in fundamentally aerobic techniques such as land treatment, some odors may occur for a short time betwen application of wastes and its complete incorporation into the soil. Generally, the best method to avoid odors in land treatment is subsurface injection.

If odors are present, even after attempts to prevent the formation or release of odorous emissions, odor control agents can be used to minimize the adverse aesthetic impact. Some chemicals on the market for odor control are listed in Table 2-5 (TRD 8).

TABLE 2-5
ODOR CONTROL AGENTS

Type of Agent	Function
Disinfectants	To kill the micro-organisms producing the odorous compounds;
Chemical Oxidants (hydrogen peroxide)	To act as disinfectants or to supply oxygen to microbial population to change to aerobic conditions;
Deodorants and Masking Agents	To react with odorous gases to prevent their release; To impart acceptable odor; To inactivate the olfactory senses.

SECTION 3

CONTROL TECHNOLOGIES

3.1 INTRODUCTION

Control technologies, discussed in this Section, operate to confine or contain the existing region of hazardous contamination and prevent further spread. Some operate by placing barriers to contain the leachate or groundwater plume; others prevent contamination of surface or groundwater by diverting flow away from the contaminated region. Technologies for the physical removal of the source of contamination also are considered control technologies.

Individual technology discussions follow the format described in Section 1. Data requirements for all of the control technologies are summarized in Table 3-1. Data which are of particular importance are distinguished from data which are less vital to technology design. In addition, common sources for these data are summarized in Table 3-2.

3.2 GROUNDWATER CONTROL TECHNOLOGIES

3.2.1 Slurry Walls

3.2.1.1 Description

Slurry walls are fixed underground physical barriers formed by pumping slurry, usually a soil or cement, bentonite, and water mixture, into a trench as excavation proceeds, and either allowing the slurry to set (for cement-bentonite, or CB slurry) or backfilling with a suitable engineered material (for soil-bentonite, or SB slurry). The slurry itself is used primarily to maintain the trench during excavation. The success of the slurry wall as a barrier depends primarily on the characteristics of the solidified CB slurry or the engineered backfill, and to a lesser extent on the thin layer of sol-

TABLE 3-1
CONTROL TECHNOLOGY DATA REQUIREMENTS

● = Useful Data
◆ = Required Data

REMEDIAL ACTION	Geography			Geology					Soils										Climatology						Groundwater							Surface Water					Waste Description			Reg	Other
	Topography	Accessibility of Site or Materials	Vegetation Characteristics	Rock Type	Structural Characteristics	Thickness of Strata	Depth to Impermeable Strata	Hydraulic Conductivity	Type (Texture)	Grain Size Distribution	Compaction	Strength Properties	Erosion Potential	Moisture Content	Permeability	Porosity	Depth	Chemistry	Precipitation (rainfall parameters)	Evapotranspiration	Storm Characteristics	Wind Characteristics	Temperature	Air Quality	Depth to Watertable	Potentiometric Surfaces	Direction and Rate of Flow	Recharge Quantity	Aquifer Characteristics	Chemistry	Infiltration	Runoff	Depth of Flow	Drainage Area	Flood Characteristics	Sedimentation	Chemical Characteristics	Physical Characteristics	Disposal Practices	Regulations	Other
GROUNDWATER																																									
slurry wall	●	◆		●	●	●	◆	●	◆	◆	●	●		◆	◆	●	●	●	●	●					◆		◆		●	◆	●						◆		●	●	◆
grout curtain	●	◆		●	●	●	◆	●	●	◆	●			◆	◆	◆	●	◆	●	●					◆		◆		●	◆	●						◆		●	●	◆
sheet pile	●	●		●	●	●	◆	●	●	◆	◆				●	●	●	●	●	●					◆		●		●	◆	●						◆		●	●	◆
block displacement	●	◆	●	◆	◆	◆	◆	◆	◆	◆	●	◆		●	◆	◆	◆	◆	●		●				◆		◆		◆	◆	◆	●			●		◆		●	●	◆
pumping	●	●				●	◆	●	◆	◆	●			●	●		●								◆	◆	●	◆	◆	●	●						●		●	◆	◆
subsurface drains	●	●				●	◆		●	●	●			●	◆		●								◆		●		●	◆	●			◆			◆		●	●	
SURFACE WATER																																									
dikes – flood	◆	◆	●		●		◆	●	◆	●	●	◆	◆		●				●	●	●	◆			●						●	●	●	●	◆	●	●	●	●	●	
dikes – runoff	◆		●						●	●	●	●	◆		●				●	●	◆										●	◆	●	◆		●				◆	
terraces	◆	●	◆						●		●	●	◆		●				●	●	◆										◆	◆	●	●		●					
channels	◆		●	●					●	●	●	●	◆		●				●	●	◆										●	◆	●	◆		●				◆	
chutes and downpipes	◆	●		●									◆						●		◆											◆	●	◆		●				◆	
grading	◆	●	●	●					●		◆	●	◆	◆	●		●		●	●	◆	●									◆	◆				●	●	●	●		◆
surface seal	●	◆	●						◆	◆	◆	◆	◆	●	◆		●	●	◆	◆	◆	◆	●	◆							◆	◆			●		◆	◆	◆	●	◆
vegetation	◆	◆	◆						◆	◆	●		●	◆	●		◆	◆	◆	●	◆	●	◆	●	●					●	◆	◆	●		◆	◆	◆	◆	◆		◆
seepage basin/ditches	●		●	●			◆		●	●	●		◆		◆		●		●	●	◆				◆			●	●	●	◆	◆		◆	●	◆				●	◆
SOIL AND WASTE																																									
excavation	◆	◆	●	●			●		●	◆	◆	●	●				◆					●		●	●												◆	◆	◆		
drum handling	●	●										●	●		●		●				●	●	●	●													◆	◆	◆		◆
encapsulation		◆																																			◆	◆			◆
dewatering	●														●				◆	◆		◆	◆	●							●	●					◆	◆			◆
AIR																																									
pipe vents	●	●							●			●	●	●	◆	●	◆		●			●	◆	●	◆						●	●			●		●	◆	◆		◆
trench vents	◆	●					●		●			●	●	●	◆	●	◆		●			●	◆	●	◆						●	●			●		●	◆	◆		◆

After: Enos, 1980

TABLE 3-2
PRIMARY DATA SOURCES

Primary Data Sources	Geography			Geology					Soils										Climatology						Groundwater							Surface Water					Waste Description			Reg.	Other
Data Sources	Topography	Accessibility of Site or Materials	Vegetation Characteristics	Rock Type	Structural Characteristics	Thickness of Strata	Depth to Impermeable Strata	Hydraulic Conductivity	Type (Texture)	Grain Size Distribution	Compaction	Strength Properties	Erosion Potential	Moisture Content	Permeability	Porosity	Depth	Chemistry	Precipitation (Rainfall Parameters)	Evapotranspiration	Storm Characteristics	Wind Characteristics	Temperature	Air Quality	Depth to Watertable	Potentiometric Surfaces[	Direction and Rate of Flow	Recharge Quantity	Aquifer Characteristics	Chemistry	Infiltration	Runoff	Depth of Flow	Drainage Area	Flood Characteristics	Sedimentation	Chemical Characteristics	Physical Characteristics	Disposal Practices	Regulations	Other
Existing Boring				●	●	●	●	●	●	●	●	●	●	●	●	●	●	●							●																
New Boring				●	●	●	●	●	●	●	●	●	●	●	●	●	●	●							●																
Survey	●																																								
Soil Map			●						●																																
Well Information																									●	●	●		●	●											
Aerial Photography	●	●	●																																		●	●			
File/Record Search			●																●		●	●				●		●	●					●			●	●	●		
Local/Private Sources		●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●						●	●	●	●	●		●	●	●			●	●	●	●	●	
Publications, Literature Search				●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●					●			●			●	●				●	●	●	●		
Site Inspection	●		●																		●	●		●																	
NOAA Data																			●	●	●	●	●											●							
Federal or State Agencies					●					●														●						●				●	●	●				●	
MAPS (OR DATA)																																									
Topography	●																															●									
USGS	●																								●	●				●	●	●									
SCS									●	●	●	●	●	●	●	●	●	●													●	●									
SGS				●	●	●	●	●																																	
DOT	●																																								
USDA									●																																
Local	●	●																																●							
Drainage																																●		●							

After: Enos, 1980

idified slurry (or filter cake) that adheres to the trench wall during construction. Slurry walls can be used to:

- contain contaminated groundwater;
- divert a contaminated groundwater plume away from a drinking water intake or towards a treatment facility;
- divert uncontaminated groundwater flow around a (potentially) contaminated area; and
- provide a hydrologic barrier for a groundwater treatment system.

A typical slurry wall is shown in Figure 3-1

3.2.1.2 Status

Conventional, demonstrated. However, new techniques are being developed.

3.2.1.3 Feasibility and Effectiveness

General

Slurry wall characteristics should be compatible with in situ soil, groundwater, and leachate conditions.

Permeability of the entire wall depends both on the formation of a filter cake on the trench wall during construction and on the backfill used. Total permeability of the wall (k) is given by the equation in Figure 3-2. (D'Appolonia, 1980). This equation is plotted in Figure 3-2 for various values of k_c/t_c. As can be seen, when the backfill permeability is very low, the filter cake has little effect. However, when backfill permeabilities are higher, filter cake permeability becomes quite significant, limiting the total permeability of the wall to no more than 10^{-6} cm/sec. This result, however, assumes that a proper bentonite slurry is used and the upstream filter cake does not rupture but stays intact (D'Appolonia, 1980).

FIGURE 3-1

CONSTRUCTION OF A BENTONITE SLURRY WALL

(Source: Sommerer and Kitchens, 1980)

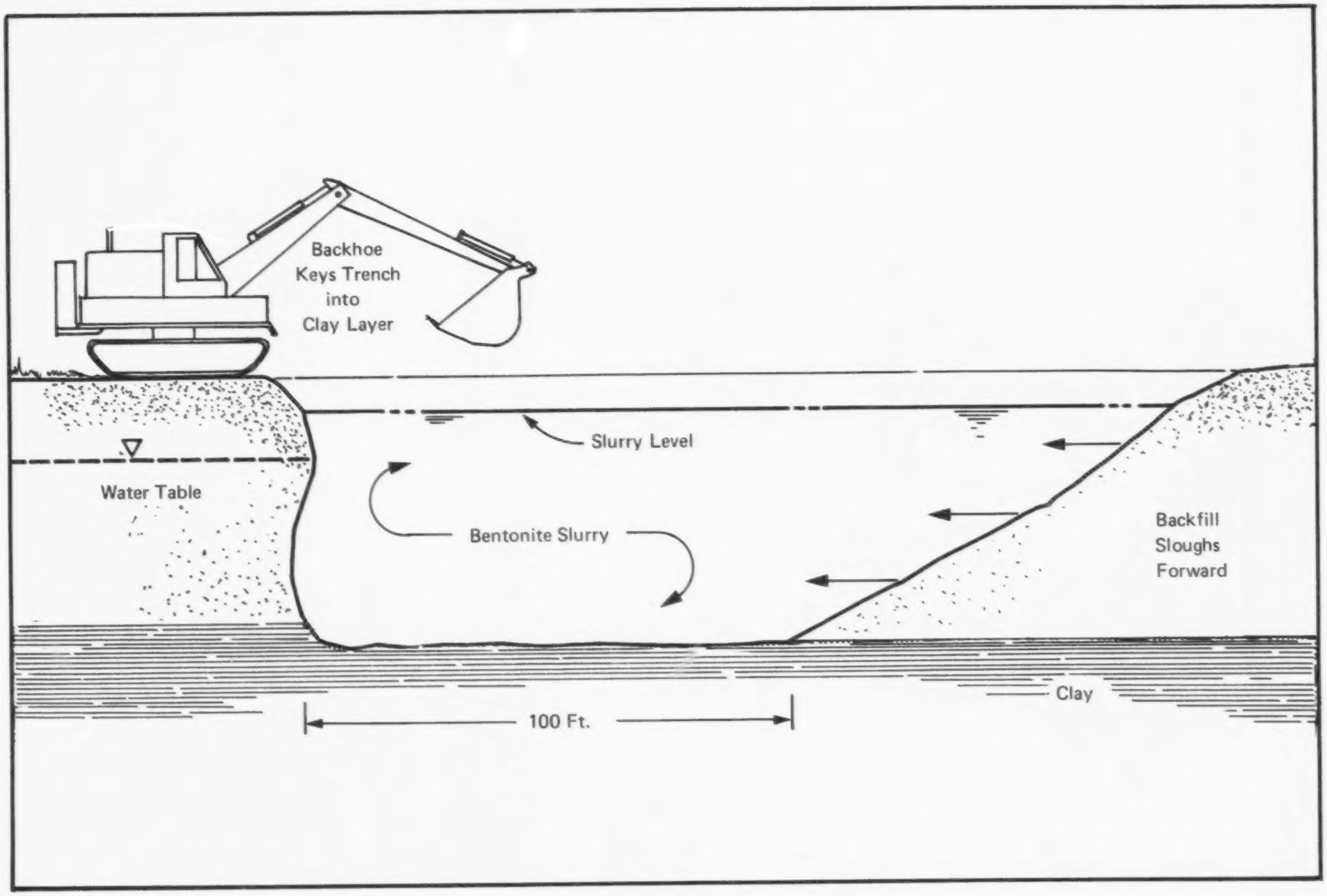

Backhoe
Keys Trench
into
Clay Layer
Slurry Level
Water Table
Bentonite Slurry
Backfill
Sloughs
Forward
Clay
100 Ft.

FIGURE 3-2

THEORETICAL RELATIONSHIP BETWEEN WALL PERMEABILITY OF FILTER CAKE AND BACKFILL

(Source: D'Appolonia, 1980)

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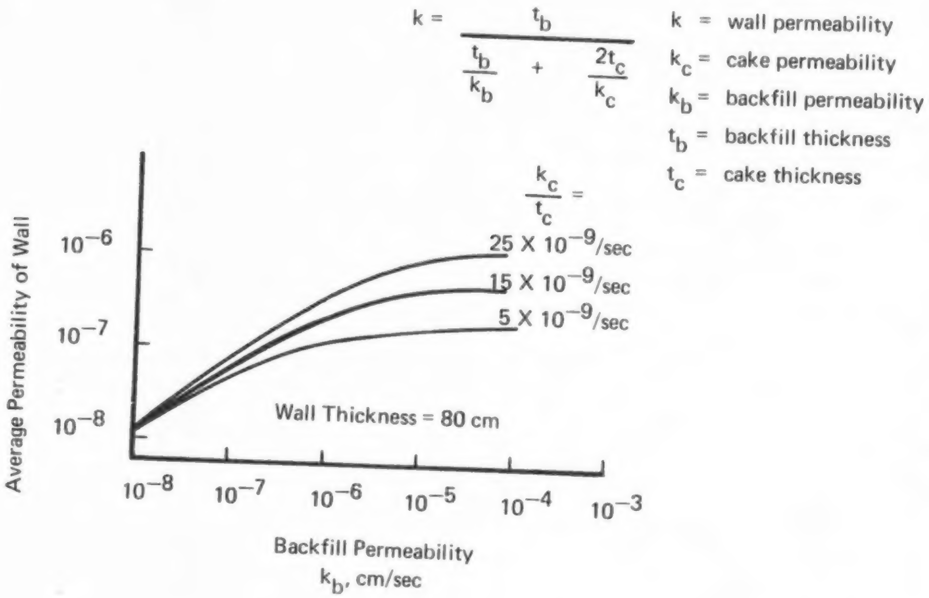

$$k = \frac{t_b}{\frac{t_b}{k_b} + \frac{2t_c}{k_c}}$$

k = wall permeability
k_c = cake permeability
k_b = backfill permeability
t_b = backfill thickness
t_c = cake thickness

Slurry walls, where possible, should extend to bedrock or a stratum with permeability as low as that of the wall to be effective. See the discussion in Section 2 concerning the use and effectiveness of impermeable barriers.

Trench Excavation

Proceeds either continuously or by panel, depending on equipment used, backfill characteristics, shape of wall, and other site-specific conditions.

Minimum trench width is determined by the type of equipment used for excavation. For all equipment, a minimum width of .6 meters (2 feet) is recommended (D'Appolonia, 1980).

Continuity of the excavation should be checked prior to backfilling. In particular, the trench should extend at least .6 meters (2 feet) into underlying soil material, and underlying rock surfaces should be scraped clean by excavating tools. Accumulated sediment from the slurry, however, does not need to be removed unless it is significantly different from the backfill material (D'Appolonia, 1980).

Slurry Characteristics

The most important slurry property is viscosity. A minimum viscosity of 40 sec-Marsh is usually needed for trench stability and good filter cake formation (D'Appolonia, 1980). Density (unit weight) and volume are also important slurry properties.

Unit weight of SB slurry should be 240 kg/m^3 (15 lb/ft^3) lighter than the backfill material for the backfill to properly displace the slurry. Typical SB slurry is, therefore, 1440 to 1680 kg/m^3 (90 to 105 lb/ft^3). Unit weight for CB slurry is usually around 1920 kg/m^3 (120 lb/ft^3). Density, however, is not as important as for SB slurry, since no backfilling is required. CB slurry achieves final set within 90 days of placement (Sommerer and Kitchens, 1980).

Volume of slurry required, as suggested by Xanthakos (1979) is:

$$V_s = \frac{Ve}{n} + \frac{Ve}{n}\left(1 - \frac{k_1}{100}\right)(n - 1) + \frac{k_2}{100}\ Ve$$

where:

Vs = volume of slurry required

Ve = total volume of excavation

n = number of panels to be constructed in the cutoff

k_1 = rate of slurry recovery during emplacement, %

k_2 = rate of slurry loss, %, during emplacement

Slurry additives may be used to modify slurry characteristics as appropriate. Additives are available to increase density, increase or decrease viscosity and gel strength, prevent flocculation, decrease fluid loss, and improve slurry circulation. For more detailed information, see Xanthakos, 1979.

Backfill Characteristics

Permeability of SB backfill material decreases with fines content (percent passing a No. 200 sieve). In addition, plastic fines result in a permeability up to two orders of magnitude lower than non-plastic or low plasticity fines (D'Appolonia, 1980). This relationship is shown in Figure 3-3.

Bentonite concentration also greatly affects backfill permeability. A minimum bentonite content of 1 percent with at least 20 percent fines is recommended. To make sure that the backfill contains adequate bentonite, either water content of the soil prior to mixing with bentonite slurry should be controlled, or dry bentonite should be added (D'Appolonia, 1980).

When compressibility and strength of the slurry wall is important, e.g., under a levee, SB backfill should be granular with 20 to 40 percent plastic or clayey fines. This optimizes permeability and compressibility (D'Appolonia, 1980).

Backfill consistency at time of placement should correspond to a slump test reading of 50 to 150 mm (D'Appolonia, 1980). In the slump test, the backfill is molded into a cone 12-inches high with an 8-inch diameter base and a 4-inch diameter top (ASTM Specification C143). The change in height of the cone after the mold is removed is the measured slump (Merritt, 1976). In addition, backfill should be placed or poured, not dropped, into the trench to avoid trapping pockets of slurry and separating of coarse and fine soils (Sommerer and Kitchens, 1980).

Special Precautions and Limitations

The bentonite should be completely hydrated and well-mixed with the soil or cement before being placed into the trench (Sommerer and Kitchens, 1980).

Compatibility of backfill materials with leachate should be carefully tested. In particular, it should be determined whether the bentonite or the soil matrix tend to dissolve in the leachate. Backfill material should be chosen to minimize the effect of the leachate. Adjusting the content of plastic fines can keep changes in permeability due to leachate within tolerable limits. In addition, it may be preferable to use soils that are already contaminated in the backfill since they may undergo less alteration

FIGURE 3-3

PERMEABILITY OF SOIL-BENTONITE BACKFILL RELATED TO FINES CONTENT
(Source: D'Appolonia, 1980)
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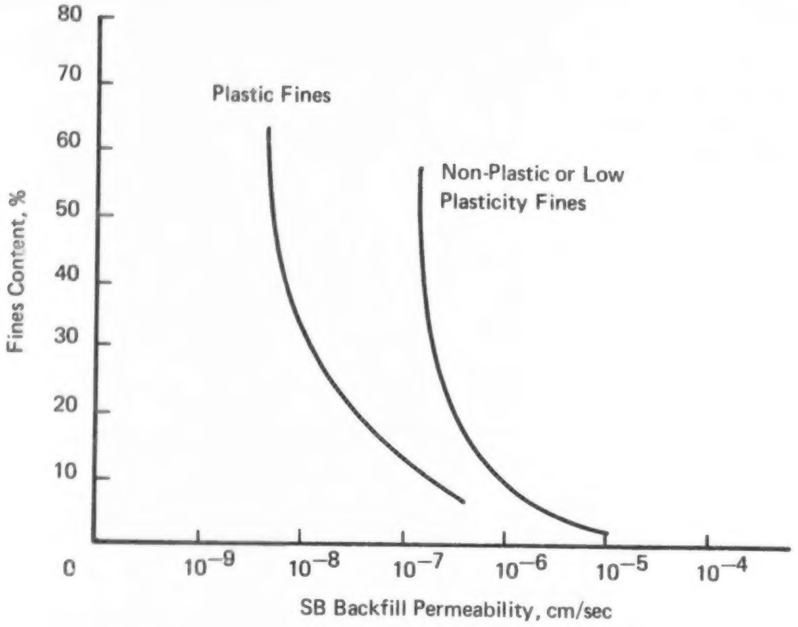


due to leachate permeation (D'Appolonia, 1980). The effect of the contaminated soil on the backfill and the filter cake, however, should be carefully tested. The effect of various pollutants on SB backfill permeability is given in Table 3-3.

3.2.1.4 Principal Data Requirements

Accessibility of suitable soil and bentonite (cost, implementability)

Depth to low-permeability stratum or bedrock (optimal depth of wall)

Soil characteristics (suitability of soil for use in SB slurry or backfill; expected lifetime and effectiveness of the wall):

- texture - granular or cohesive

TABLE 3-3
PERMEABILITY INCREASE DUE TO LEACHING WITH VARIOUS POLLUTANTS

Pollutant (1)	Filter Cake (2)	SB Backfill (silty or clayey) sand) 30% to 40% Fines (3)
CA++ or Mg++ at 1,000 ppm	N	N
CA++ or Mg++ at 10,000 ppm	M	M
NH_4NO_3 at 10,000 ppm	M	M
HCL (1%)	N	N
H_2SO_4 (1%)	M	N
HCL (5%)	M/H[a]	M/H[a]
NaOH (1%)	M	M
CaOH (1%)	M	M
NaOH (5%)	M	M/H[a]
Sea water	N/M	N/M
Brine (SG = 1.2)	M	M
Acid mine drainage ($FeSO_4$; pH ∿ 3)	N	N
Lignin (in CA++ solution)	N	N
Alcohol	H (failure)	M/H

[a] Significant dissolution likely.

Note: N = no significant effect, permeability increase by about a factor of 2 or less at steady state; M = moderate effect, permeability increase by factor of 2 to 5 at steady state; H = permeability increase by factor of 5 to 10.

Source: D'Appolonia, 1980

- grain size distribution and gradation
- moisture content
- permeability
- soil pressure

Groundwater characteristics (construction requirements, such as additives and required strength; lifetime of wall)

- depth to water table
- direction and rate of flow

- pH
- hardness
- salt concentration
- presence of other minerals and organics
- water pressure
- leachate chemistry

3.2.1.5 Elements of Cost Review

Components

Construction and Capital--

- laboratory and field testing
- trench excavation
- slurry mixing
- backfilling
- transportation of material
- slurry material
- backfill material
- slurry additives

O & M--

- Monitoring

Major Factors

- excavation method

- length and depth of wall
- transportation distance for bentonite, other soil
- type of slurry and backfill used

Data

Unit costs for a slurry wall are usually given in square feet (length x depth). When a backhoe can be used for excavation, a unit cost as low as \$2-3/ft^2 is possible. Depending on other factors, costs may be as high as \$8-10/ft^2.

3.2.2 Grout Curtains

3.2.2.1 Description

Grout curtains are fixed underground physical barriers formed by injecting grout, either particulate (such as Portland cement) or chemical (such as sodium silicate), into the ground through well points. Grout curtains can be used to:

- contain contaminated groundwater;
- divert a contaminated groundwater plume away from a drinking water intake or towards a treatment facility; and
- divert uncontaminated groundwater flow around a (potentially) contaminated area.

3.2.2.2 Status

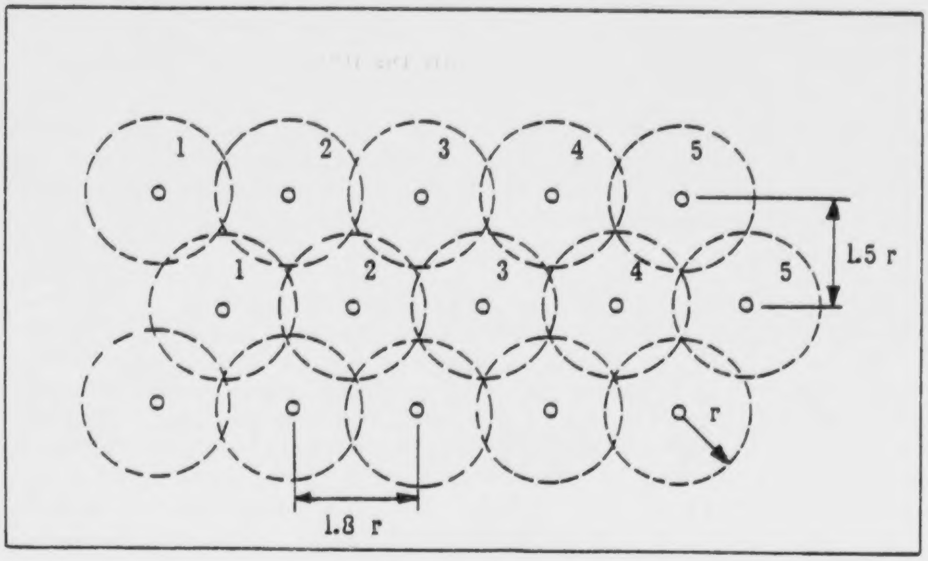
Conventional, undemonstrated. Grout curtains are useful only under certain site specific conditions, and it is difficult to verify whether a contiguous curtain has been formed.

3.2.2.3 Feasibility and Effectiveness

FIGURE 3-4

TYPICAL THREE-ROW GRID PATTERN FOR GROUT CURTAIN

(Source: Sommerer and Kitchens, 1980)



Construction

Grout curtains are typically formed by injecting grout through pipes in a pattern of two or three adjacent rows, as shown in Figure 3-4.

Pipe spacing depends on the radial distance of grout penetration, r (cm), where:

$$r = .62 \sqrt[3]{\frac{Q\ t}{n}}$$

and:

Q = rate of grout injection (cm^3/min)

n = porosity of soil (unitless)

t = pumping time or gelation time (min)

Space between ajacent pipes should be $\sim 2r$ (Sommerer and Kitchens, 1980).

The rate of injection should be carefully chosen depending on site-specific characteristics. Excessively slow rates result in premature grout/soil consolidation, and excessively rapid rates result in fracturing of the soil formation.

A variation for grout curtain installation is the vibrating beam technique. Although it is sometimes called a slurry wall technique, it is closer to a grout curtain variation since the slurry is injected through a pipe similar to grouting. A suspended I-beam, connected to a vibrator, is inserted into the ground. Slurry is then injected under pressure through a set of nozzles located at the base of the vibrated beam. At the completion of a panel, the rig is moved along the direction of the wall, and the process is repeated. The previous insertion is overlapped to provide continuity, but the barrier is only 10 cm (4 in.) thick.

Grout Material

Important characteristics of various grout materials are given in Table 3-4 and Table 3-5, and Figure 3-5. Information on bitumen grouts and other more recent polymer grouts, such as urethane and epoxy resin, is not included.

Selection of grout material depends on:

- soil permeability (see Figure 3-6);
- soil grain size (see Figure 3-7);
- rate of groundwater flow;
- chemical constituents of soil and groundwater;
- grout strength required; and
- cost

TABLE 3-4
TYPES OF GROUT

	Significant Characteristics	Cost Relative To Portland Cement
Portland Cement or Particulate Grouts	-Appropriate for higher permeability (larger grained) soils; -Least expensive of all grouts when used properly; -Most widely used in grouting across the U.S. (90% of all grouting).	1.0
Chemical Grouts		
Sodium Silicate	-Most widely used chemical grout -At concentrations of 10-70% gives viscosity of 1.5 - 50 cP -Resistant to deterioration by freezing or thawing; -Can reduce permeabilities in sands from 10^{-2} to 10^{-8} cm/s; -Can be used in soils with up to 20% silt and clay at relatively low injection rates; -Portland cement can be used to enhance water cutoff	0-5.0
Phenoplasts	-Rarely used due to high cost -Should be used with caution in areas exposed to drinking water supplies; -Low viscosity; -Can shrink (with impaired integrity) if excess (chemically unbound) water remains after setting; unconfined compression strength of 50-200 psi in stabilized soils.	N.A.
Lignosulfonate Derivatives	-Rarely used due to high toxicity -Lignin can cause skin problems and hexavalent chromium is highly toxic; both are contained in these materials; -Cannot be used in conjunction with Portland Cement: pH's conflict; -Ease of handling; -Lose integrity over time in moist soils; -Initial soil strengths of 50-200 psi.	1.65

(Cont.)

TABLE 3-4
TYPES OF GROUT (Cont.)

	Significant Characteristics	Cost Relative To Portland Cement
Aminoplasts e.g., urea-formaldehydes	-Rarely used due to high cost -Will gel with an acid or neutral salt; -Gel time control is good	N.A.
Acrylamid Grouts	-Rarely used due to toxicity -Should be used with great caution near to drinking water supplies; -Readily soluble in water; -Manufacter in USA prohibited available as AV-100 from Japan; -Can be used in finer soils than most grouts because low viscosities are possible (1 cP); -Excellent gel time control due to constant viscosity from time of catalysis to set/gel time; -Unconfined compressive strengths of 50-200/psi in stabilized soils; -Gels are permanent below the water table or in soils approaching 100% humidity; -Are vulnerable to freeze-thaw and wet-dry cycles, particularly where dry periods predominate and will fail mechanically; -Due to ease of handling (low viscosity), enables more efficient installation and is often cost-competitive with other grouts.	4.0-10.0

Specific grout products and their properties are listed in Table 3-5.

From: Kirk and Othmer, 1979; Sommerer and Kitchens, 1980; and GZA, 1982

TABLE 3-5
GROUT PROPERTIES

GROUT MATERIAL	CATALYST MATERIAL	UNCONFINED COMPRESSIVE STRENGTH (PSI) OF GROUTED SOIL	VISCOSITY (CENTIPOISE)	SETTING TIME MINUTES	TOXICANT*	POLLUTANT**
SILICATE BASE						
LOW CONCENTRATION	BICARBONATE	10-50	1.5	0.1-300	NO	NO
LOW CONCENTRATION	HALLIBURTON CO. MATERIAL	10-50	1.5	5-300	NO	NO
LOW TO HIGH CONCENTRATION	SIROC-DIAMOND SHAMROCK CHEMICAL CO.	10-500	4-40	5-300	NO	NO
LOW TO HIGH CONCENTRATION	CHLORIDE-JOOSTEN PROCESS	10-1000	30-50	0	NO	NO
LOW TO HIGH CONCENTRATION	ETHYL-ACETATE SOLETANCHE & HALLIBURTON	10-500	4-40	5-300	NO	NO
LOW TO HIGH CONCENTRATION	RHONE-PROGIL 600	-	-	-	-	-
LOW TO HIGH CONCENTRATION	GELOC-3 H. BAKER CO.	10-500	4-25	2-200	NO	NO
LOW TO HIGH CONCENTRATION	GELOC-3X	10-250	4-25	0.5-120	NO	NO
LIGNIN BASE						
BLOX-ALL	HALLIBURTON CO. MATERIAL	5-90	8-15	3-90	YES	YES
TDM	CEMENTATION CO. MATERIAL	50-500	2-4	5-120		
TERRA-FIRMA	INTRUSION CO. MATERIAL	10-50	2-5	10-300	YES	YES
LIGNOSOL	LIGNOSOL CO. MATERIAL	10-50	50	10-1000	YES	YES
FORMALDEHYDE BASE						
UREA-FORMALDEHYDE	HALLIBURTON CO. MATERIAL	OVER 1000	10	4-60	YES	YES
UREA-FORMALDEHYDE	AMERICAN CYANAMID CO. MATERIAL	OVER 500	13	1-60	YES	YES
RESORCINOL FORMALDEHYDE	CEMENTATION CO. MATERIAL	OVER 500	3.5	-	YES	YES
TANNIN-PARA-FORMALDEHYDE	BORDEN COMPANY MQ-8					
GEOSEAL MQ-4 & MQ-5	BORDEN COMPANY MATERIAL					
UNSATURATED FATTY ACID BASE						
POLYTHIXON FRD	CEMENTATION CO. MATERIAL	OVER 500	10-80	25-360	NO	NO

* - A material which must be handled using safety precautions and/or protective clothing.

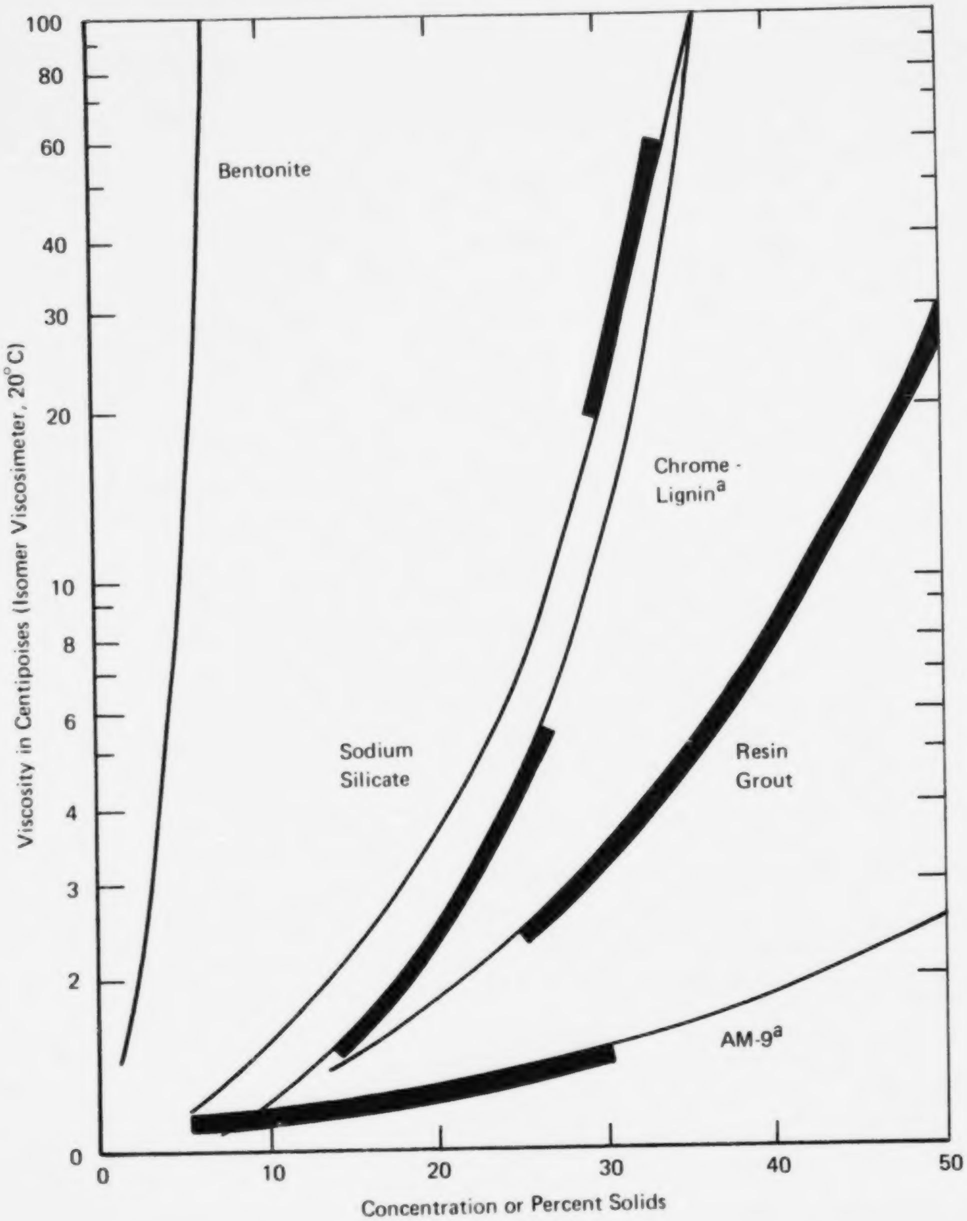
** - Pollutant to fresh water supplies contacted.

Source: Hallburton Services, 1976

FIGURE 3-5

VISCOSITIES OF VARIOUS GROUTING MATERIALS AS A FUNCTION OF GROUT CONCENTRATION (the solid lines represent the concentration normally used)

(Source: Sommerer and Kitchens, 1980)



a. No longer manufactured.

FIGURE 3-6
CORRELATIONS BETWEEN SOIL GRAIN SIZE, PERMEABILITY AND POTENTIAL DEWATERING METHODS
(Source: Sommerer and Kitchens, 1980)

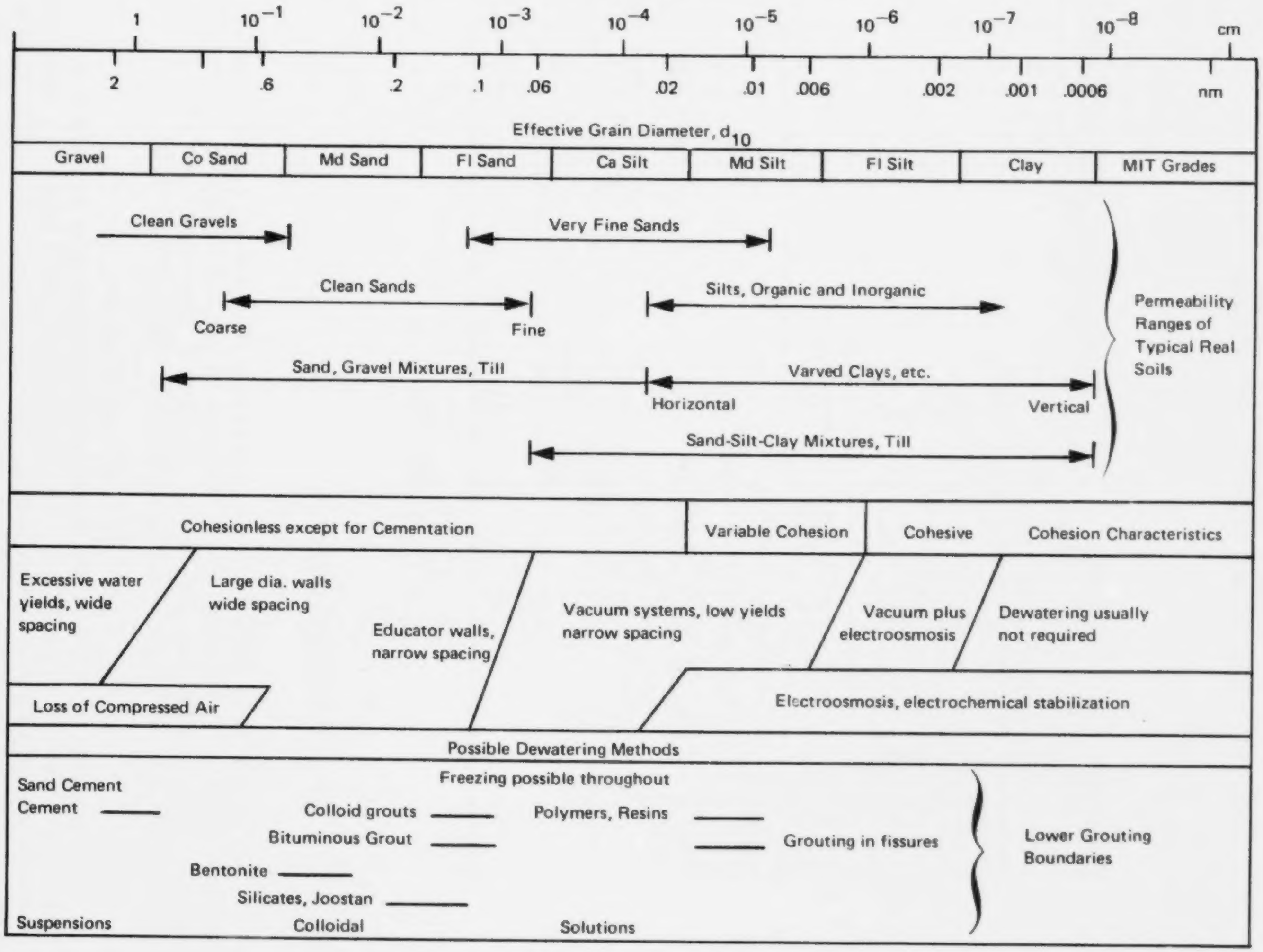

1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
cm
2
.6
.2
.1
.06
.02
.01
.006
.002
.001
.0006
nm
Effective Grain Diameter, d10
Gravel
Co Sand
Md Sand
Fl Sand
Ca Silt
Md Silt
Fl Silt
Clay
MIT Grades
Clean Gravels
Very Fine Sands
Clean Sands
Coarse
Fine
Silts, Organic and Inorganic
Sand, Gravel Mixtures, Till
Varved Clays, etc.
Horizontal
Vertical
Sand-Silt-Clay Mixtures, Till
Permeability Ranges of Typical Real Soils
Cohesionless except for Cementation
Variable Cohesion
Cohesive
Cohesion Characteristics
Excessive water yields, wide spacing
Large dia. walls wide spacing
Educator walls, narrow spacing
Vacuum systems, low yields narrow spacing
Vacuum plus electroosmosis
Dewatering usually not required
Loss of Compressed Air
Electroosmosis, electrochemical stabilization
Possible Dewatering Methods
Freezing possible throughout
Sand Cement
Cement
Colloid grouts
Polymers, Resins
Bituminous Grout
Grouting in fissures
Bentonite
Silicates, Joostan
Lower Grouting Boundaries
Suspensions
Colloidal
Solutions

FIGURE 3-7
SOIL GRAIN SIZE LIMITS FOR GROUT INJECTABILITY
(Source: Haliburton Services, 1976)
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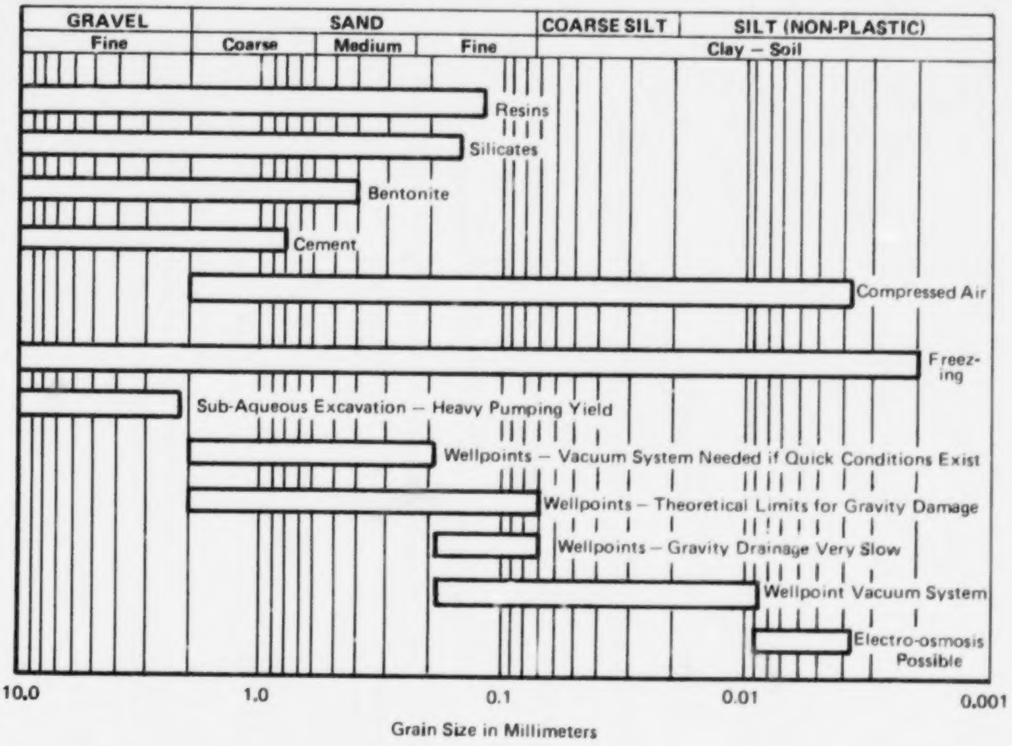


In situ Requirements

Soil is not considered suitable for grouting if more than 20 percent of the soil passes through a No. 200 sieve. Low viscosity grouts are required if more than 10 percent of the soil passes through a No. 200 sieve (Sommerer and Kitchens, 1980).

Groundwater flow can adversely affect the integrity of a grout curtain, particularly during construction. Special consideration should be given to rate of flow and chemical composition of the groundwater (Sommerer and Kitchens, 1980).

Special Precautions and Limitations

Grout curtains should extend to an impervious (or bedrock) layer to be effective. See discussion in Section 2 concerning use and effectiveness of groundwater barriers.

Maximum effective depth is limited by depth of the injection well or site specific constraints.

3.2.2.4 Principal Data Requirements

Accessibility of grout equipment and materials (implementability and cost)

Depth to low permeability stratum or bedrock (optimal depth of wall)

Soil characteristics (soil groutability, grout penetration, rate of injection, grout material selection)

- grain size distribution
- moisture content
- permeability
- porosity
- chemistry

Groundwater characteristics (grout material selection, wall construction)

- depth to water table
- direction and rate of flow
- pH
- concentration of sulfides, calcium
- leachate chemistry

Grout characteristics (barrier performance)

- strength properties

- viscosity
- gelation time

3.2.2.5 Elements of Cost Review

Components

Construction and Capital--

- laboratory and field testing
- well drilling
- grout injection
- grout material

O & M--

- Monitoring

Major Factors

- length and depth of wall
- number of wells per row of grid pattern
- number of rows in grid pattern
- grout material

Data

Unit costs of various grout materials are given in Table 3-6.

Total cost for a grout curtain 720 meters (2400 ft.) long and 15 meters (49 ft.) deep with a 2-row grid chemical grout and wells every 1.8 meters (6 ft.), in 1982 dollars, is 7.5 million to 15.1 million dollars, or 231 to 466 $\$/m^3$ of grout curtain.

TABLE 3-6
UNIT COSTS OF GROUTS

Grout Type	Approximate Cost, 1982 Dollars $/Gallon of Solution
Portland Cement	1.05
Bentonite	1.38
Silicate - 20%	1.93
- 30%	2.31
- 40%	3.03
Lignochrome	1.71
Acrylamide	7.32
Urea Formaldehyde	6.27

Source: EPA, 1982

3.2.3 Sheet Pile Cutoff Walls

3.2.3.1 Description

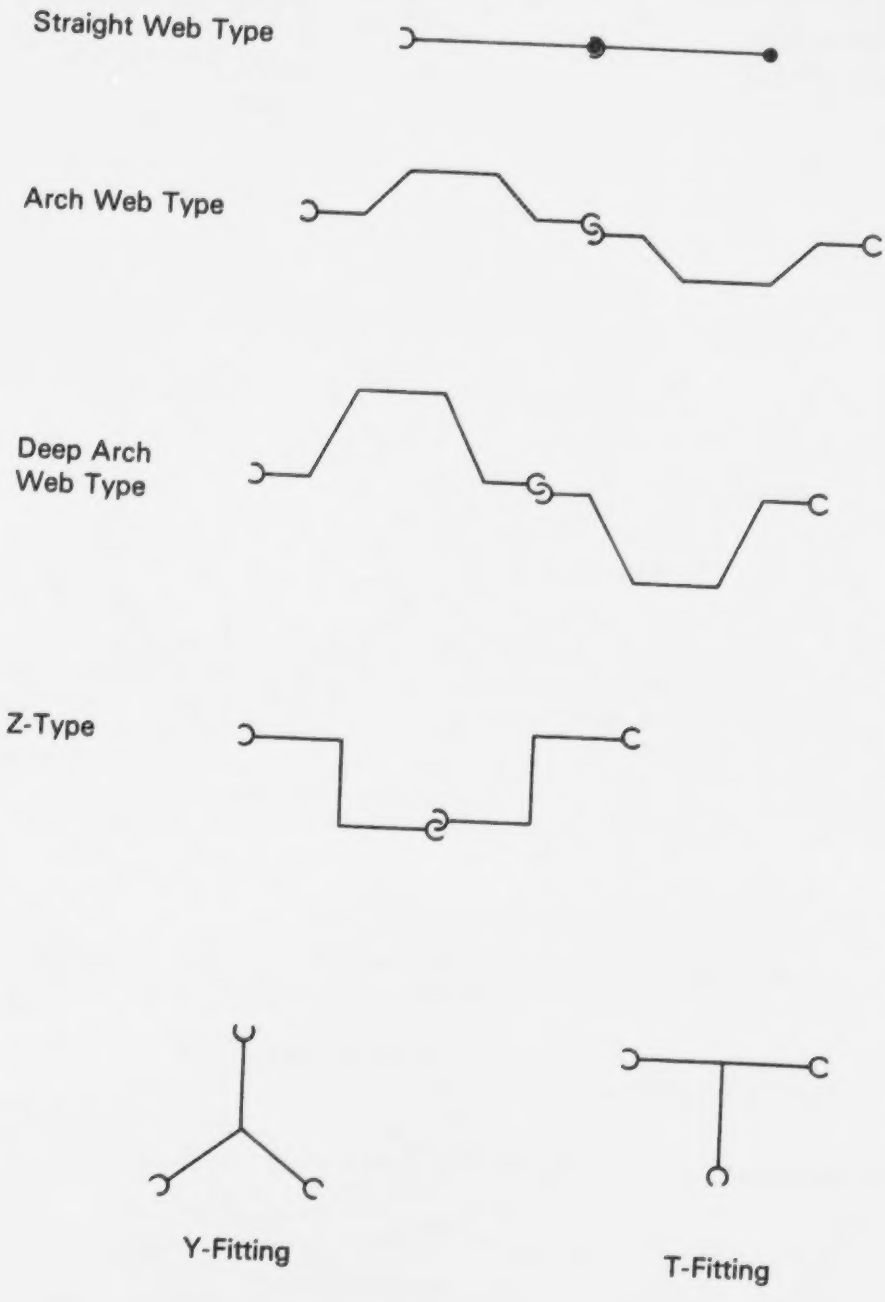
Sheet piling cutoff walls are constructed by driving web sections of sheet piling permanently into the ground. Each section is interlocking at its edges by either a socket or bowl and ball joint. Sections are assembled before being driven into the ground and initially are not watertight. However, the joint connections soon fill with fine- to medium-grained soil particles, generally blocking groundwater flow. Sheet piling cutoff walls can be used to:

- contain contaminated groundwater;
- divert a contaminated plume away from a drinking water intake or towards a treatment facility; and
- divert uncontaminated groundwater flow around a (potentially) contaminated area.

Various sheet pile cross-sections are shown in Figure 3-8.

FIGURE 3-8

SHEET PILING SECTION PROFILES
(Source: EPA, 1982)


Straight Web Type
Arch Web Type
Deep Arch Web Type
Z-Type
Y-Fitting
T-Fitting

3.2.3.2 Status

Conventional, demonstrated.

3.2.3.3 Feasibility and Effectiveness

General

Maximum effective depth is considered to be 15 meters (49 ft), although pile sections have been driven up to depths of 30 meters (98 ft)(Sommerer and Kitchens, 1980).

Steel sheet piling is most frequently used. Concrete and wood have also been used. Concrete is expensive but is attractive when exceptional strength is required; and, although less expensive, wood is relatively ineffective as a water barrier (EPA, 1982).

Sheet piles are typically used in soils that are loosely packed and predominantly sand and gravel in nature. A penetration resistance of 4 to 10 blows/foot for medium- to fine-grained sand is recommended (Terzaghi and Peck, 1948).

Piling lifetime depends on waste characteristics and pile material. For steel piles pH is of particular importance. Ranges of pH from 5.8 to 7.8 enables a lifetime up to 40 years (depending on other leachate characteristics), and pH as low as 2.3 can shorten the lifetime to 7 years or less (EPA, 1982).

Special Precautions and Limitations

Sheet pile cutoff walls should extend to bedrock or other impermeable strata to be effective. See the discussion in Section 2 concerning the use and effectiveness of groundwater barriers.

3.2.3.4 Principal Data Requirements

Depth to low-permeability stratum or bedrock (optimal depth of wall)

Soil characteristics (soil suitability for sheet pile use)

- grain size distribution
- compaction

Groundwater characteristics (pile lifetime, placement)

- depth to water table
- pH
- leachate chemistry

3.2.3.5 Elements of Cost Review

Components

Construction and Capital--

- installation
- shipping
- piling material

O & M--

- Monitoring

Major Factors

- length and depth of wall
- piling material used

Data

Unit costs for sheet piling and installation are shown in Table 3-7.

TABLE 3-7
SHEET PILING UNIT COSTS

	Assumptions	1982 Costs
Sheet Piling	Black steel	$1,300/ton
	Hot dipped galvanized steel	1,500/ton
	(5 gage dimensions: 19.6 in. laying width, 3.18 in. front to back, and 20 ft. long)	
	Installation	280/ton

Source: EPA, 1982

Total cost for a sheet piling cutoff wall 720 meters (2360 ft) long and 15 meters (49 ft) deep in 1982 dollars is $612,000 to 902,000 (SCS, 1980).

3.2.4 Block Displacement Method (BDM)

3.2.4.1 Description

Block Displacement is a method for placing a fixed underground physical barrier around and beneath a large mass of earth (called a block). The bottom barrier is formed when fractures (or separations) extending from horizontal notches at the base of the injection holes coalesce into a larger separation beneath the mass block of earth. Continued pumping of slurry under pressure produces a large uplift force against the bottom of the block and results in vertical displacement proportional to the volume of slurry pumped.

A perimeter barrier around the block is constructed by conventional techniques in conjunction with the bottom barrier either prior to or following bottom barrier construction. The perimeter wall constructed prior to bottom separation can be used to ensure a favorable horizontal stress field for proper formation of the bottom separation. In geologic formations not requiring control of horizontal stress, the perimeter may be constructed following initial bottom separation or following the completion of block lift.

The Block Displacement Method can be used to:

- contain contaminated groundwater;
- divert uncontaminated groundwater flow around a (potentially) contaminated area; and
- lower the water table inside the isolated area.

A typical BDM barrier is shown in Figure 3-9.

3.2.4.2 Status

Developmental. Verification of the bottom barrier is now in progress.

3.2.4.3 Feasibility and Effectiveness

General

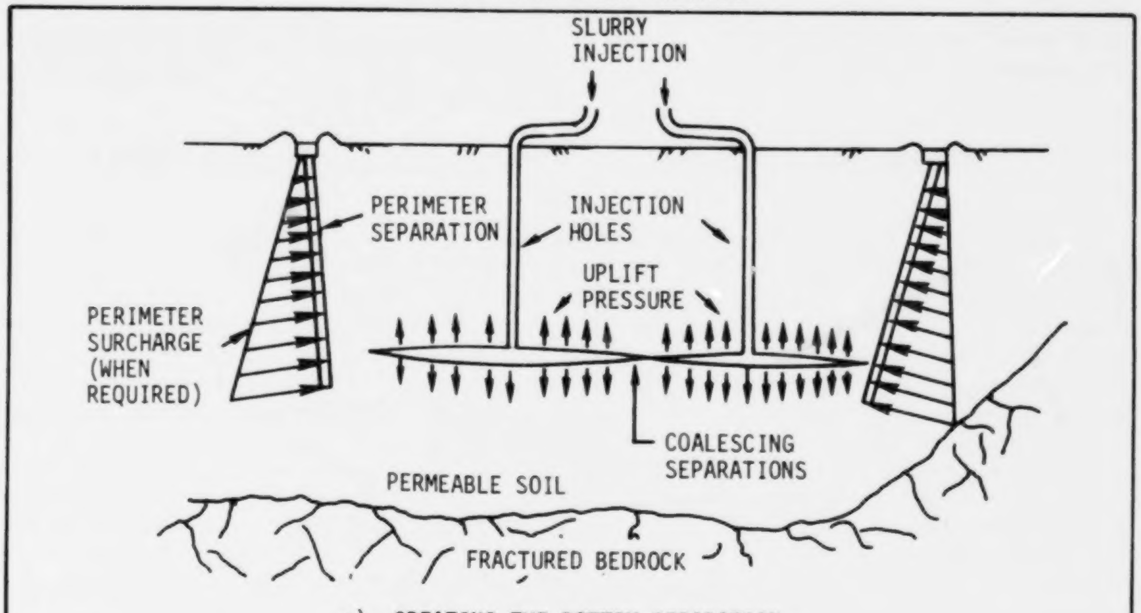
The Block Displacement Method is of particular value in stratum where unweathered bedrock or other impermeable continuum is not sufficiently near the surface for a perimeter barrier alone to act as an isolator.

Permeability of the bottom barrier depends both on the filter cake that forms on the separation surfaces and on the permeability of the residual slurry which consolidates with time. As water in the residual slurry leaks off with time, the permeability of the entire barrier approaches that of the filter cake. Permeabilities of 10^{-8} cm/sec are attainable with proper slurry design.

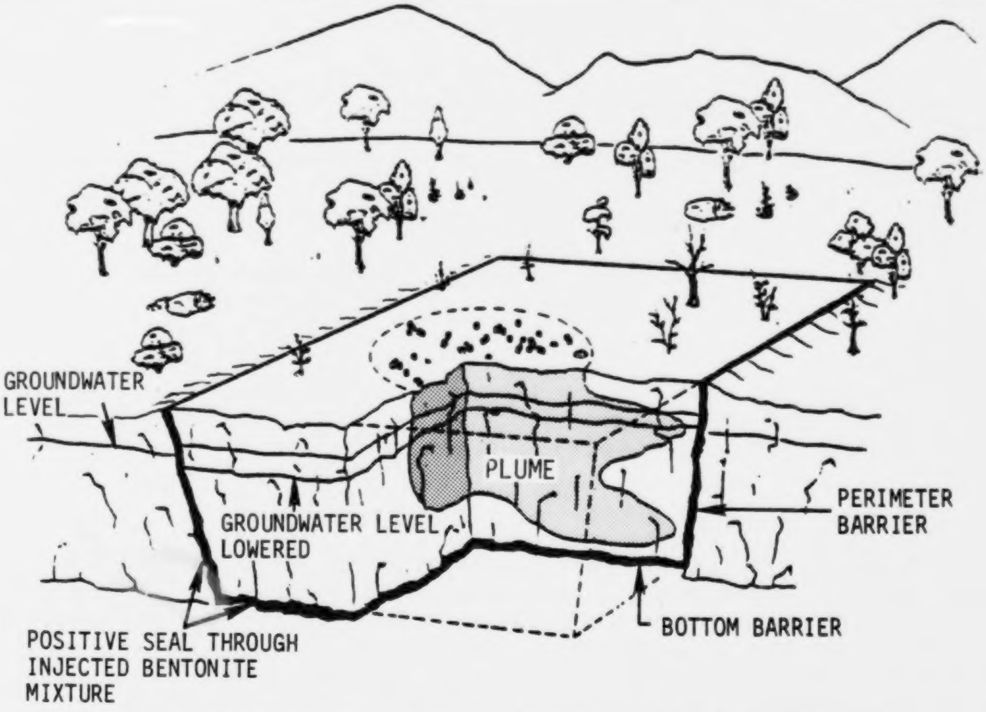
The effectiveness of the bottom barrier is based on the permeability of the consolidated slurry material and the thickness of the barrier.

FIGURE 3-9

BLOCK DISPLACEMENT METHOD


SLURRY INJECTION
PERIMETER SEPARATION
INJECTION HOLES
UPLIFT PRESSURE
PERIMETER SURCHARGE (WHEN REQUIRED)
COALESCING SEPARATIONS
PERMEABLE SOIL
FRACTURED BEDROCK

a) CREATING THE BOTTOM SEPARATION


GROUNDWATER LEVEL
PLUME
PERIMETER BARRIER
GROUNDWATER LEVEL LOWERED
BOTTOM BARRIER
POSITIVE SEAL THROUGH INJECTED BENTONITE MIXTURE

b) CONFIGURATION OF FINAL BOTTOM AND PERIMETER BARRIERS

Effectiveness of the perimeter barrier is dependent on the perimeter construction technique. (See other sections describing groundwater barrier techniques.) In general the perimeter should be designed with an overall effectiveness compatible with the effectiveness of the bottom barrier.

Bottom Barrier Construction (Brunsing, et.al., 1982)

Construction of the bottom barrier proceeds in four phases: (1) Formation of notches at the base of the injection holes; (2) Initial bottom separation at the notched holes; (3) Propagation of the local separations at each injection point coalescing into a single larger bottom separation; (4) Generation of a complete bottom barrier by controlled vertical displacement of the earth mass using low pressure slurry injection into the horizontal separation. Each of the these phases is carried out through control and monitoring of slurry pressure, slurry flow rate, total volume injected, and slurry composition. The notching operation (1) requires a high pressure rotating jet at the base of the injection. The jetting slurry must be composed in a manner which optimizes notch erosion, removes cuttings, and minimizes leak off into the soil. The initiation of bottom separation (2) requires a slurry pressure, P_O, defined by:

$$P_O = \rho_r gh + \Delta P$$

where: ρ_r is the average earth mass density

g is the gravitational constant

ΔP is the pressure in excess of the overburden

h is the depth of the bottom separation

ΔP increases with increasing slurry viscosity and decreasing notch radius and in general depends on soil characteristics. The bottom separation is initiated when a slurry flow at a fixed P_O occurs.

Separation coalescence (3) is brought about by adding slurry volume and by gradually increasing the viscosity of the slurry. Slurry pressure required to propagate the horizontal separation will reduce during this phase due to the increased area over which it is acting. Increasing the viscosity of the slurry serves to limit flow in preferential directions.

Vertical displacement (4) utilizes the maximum capacity of the pumping equipment, along with a high solids slurry that will form the final barrier. The pressure required to continuously increase the barrier thickness by lifting the buoyed block eventually decreases. When a perimeter barrier is constructed prior to displacement, the injection pressure approaches that required to balance the resistance of the fluid in the perimeter (ΔP_2) and to overcome fluid drag in the bottom separation (ΔP_1) (Cleary, 1979). The final pressure relationship is:

$$\Delta P_2 + \frac{\Delta P_1}{n} = (\rho_r - \rho_m) \quad g$$

where: ρ_m is the density of the mud in the perimeter barrier

n depends on the number of injection holes
(= 3 for a single central hole)

Bottom barrier construction proceeds simultaneously or by section from multiple injection points depending on size of site, geology, and perimeter barrier technique used.

Bottom barrier thickness can vary from a few centimeters to more than a meter. The thickness is increased by further pumping of slurry down injection holes. Selective pumping coupled with a high viscosity slurry design enables relative variation or adjustment to bottom barrier thickness during block displacement.

Continuity of the bottom barrier can be checked by pressure communication between injection holes and by surface level survey during block displacement.

Verification of barrier completeness can be attained following perimeter and bottom construction by long term monitoring of draw down within the isolated block. If deemed necessary, continued pumping can further increase the bottom thickness locally or in general until satisfactory verification results are attained.

Perimeter Barrier Construction

Construction of the perimeter barrier begins with the construction of a perimeter separation which can proceed using one of several standard techniques, as mentioned earlier. The thickness of the perimeter separation can be less than the final thickness, by placing the separation at a small angle to the vertical so that the sides are convergent downward. Thus, the thickness of the sides will increase by w when the block is vertically displaced by d according to:

$$w = d \sin \phi$$

where ϕ is the angle of the perimeter barrier measured from the vertical.

The perimeter separation must be made deep enough to intersect the bottom separation. If the perimeter is installed after the bottom separation is created, the intersection will be determmined when slurry flows from the bottom up the perimeter. If the perimeter separation is installed prior to the bottom separation, it must be made deep enough to insure that this intersection will take place. In certain soil conditions, creating the bottom separation requires the use of heavy mud in the perimeter separation to add horizontal stress in the block. Under these conditions the perimeter separation must be made deep enough so that the horizontal stress can be fully transmitted through the block at the bottom separation level.

Slurry Characteristics

The various functions of the slurries used can be summarized as follows:

1. Bottom Barrier Construction
    - notching
    - initiating bottom separation
    - propagation and coalescing of bottom separation
    - block lift and final barrier construction
2. Perimeter Barrier Construction
    - soil stabilization during construction of perimeter separation

- pressure surcharge for increasing horizontal stress
- gel strength to resist leak off during block lift and final barrier construction

Table 3-8 lists these various functions along with the range of slurry properties applicable to each function. The quality requirements for the material representing the final barrier are equivalent to those for other bentonite clay based barrier and sealing techniques (see Table 3-3).

Special Precautions and Limitations

The barrier should be compatible with in-situ soil, groundwater, and leachate conditions.

3.2.4.4 Principal Data Requirements

Accesibility of Suitable Soil and Bentonite (cost and implementability)

Soil characteristics (suitability of soil for use in soil bentonite slurry; expected lifetime and effectiveness of the barrier):

- discontinuities in soil strata in region of expected bottom barrier construction
- cohesive and consolidation states of individual strata
- degree and orientation of soil stratification and bedding
- absolute value and variation of soil permeability in individual strata
- proximity of weathered bedrocks or solution channels to expected bottom barrier region
- texture and grain size distribution
- moisture content
- soil pressure

TABLE 3-8

SLURRY CHARACTERISTICS FOR THE BLOCK DISPLACEMENT METHOD

FUNCTION	DENSITY (Sp. Gr.)	GEL STRENGTH (Pa)	PERMEABILITY WHEN CONSOLIDATED (cm/sec.)	COMMENTS
Bottom Barrier Construction i) Notching	1.1 - 1.3	10 - 20	Based on permissible leak off & soil characteristics.	Must match notching tool jet design.
ii) Initiating bottom separation	1.1 - 1.3	10	"	Low viscosity slurry desired.
iii) Propagation and coalescence	2.0 - 3.0	20 - 50	"	
iv) Lift and final barrier	1.8 - 1.9	50 - 100	10^{-7} - 10^{-8}	High viscosity but pumpable.
Perimeter Barrier Construction i) Stabilization	1.5 - 2.5	20	Based on permissible leak off & soil properties	Indicated values for med. grain sand-varies according to soil properties.
ii) Surcharge (when placed prior to lift)	1.9 - 2.0	200	"	Max. density desired, flow requirements minimal.
iii) Gel strength and final barrier	1.8 - 1.9	50 - 100	depends on thickness	Total barrier permeability and thickness should match the effectivenss of the bottom barrier.

Groundwater characteristics (construction requirements, such as additives and required strength; lifetime of barrier):

- depth of watertable
- direction and rate of flow
- pH
- hardness

3.2.4.5 Elements of Cost Review

Components

Construction and Capital--

- slurry material
- transportation of material
- drilling and casing
- notching
- slurry injection plumbing
- slurry mixing
- pumping
- instrumentation, control, and verification

O & M--

- Monitoring

Major Factors

- size of the earth mass to be displaced
- depth and thickness of bottom barrier

- construction method for perimeter barrier
- required spacing of injection holes

Data

None available.

3.2.5 Groundwater Pumping

3.2.5.1 Description

Groundwater pumping uses a series of wells to remove groundwater for treatment (if it is contaminated), subsequent discharge, or both. A well system utilizes one or more pumps to draw groundwater to the surface forming a cone of depression in the groundwater table, the extent and slope of which is dependent on pumping rates and duration as well as local groundwater and soil factors.

Groundwater pumping can be used to lower the water table and to contain a plume. It can also be utilized in conjunction with other groundwater controls (impermeable barriers or subsurface drainage systems) to maximize their efficiency. Although pumping can be expensive compared to other control technologies, it might be the most practical alternative under certain circumstances, including (Doering and Benz, 1972):

- combinations of fine and textured soils or upward hydraulic gradients make subsurface drainage difficult; and
- groundwater conditions are stagnant e.g., hydraulic gradient is nearly zero.

3.2.5.2 Status

Conventional, demonstrated.

3.2.5.3 Feasibility and Effectiveness

Drawdown

The effective drawdown (s) of a well or well system can be very difficult to estimate. The following equations are used to estimate drawdown under certain conditions (Freeze and Cherry, 1979):

- In a confined, isotropic aquifer:

$$s = \frac{Qw}{4\pi T} W(u)$$

- In an unconfined aquifer at early time (t < a few minutes):

$$s = \frac{Qw}{4\pi T} W(u_A, \eta)$$

- In an unconfined aquifer at later time (t < a few minutes):

$$s = \frac{Qw}{4\pi T} W\ (u_B, \eta)$$

where:

$$u = u_A = \frac{r^2 S}{4Tt}$$

$$u_B = \frac{r^2 Sy}{4Tt}$$

$\eta = \frac{r^2}{b^2}$ in an isotropic aquifer

$\eta = \frac{r^2 k1}{b^2 k2}$ in an anisotropic acquifer

and:

Qw = pumping rate of the well
T = transmissivity of the aquifer
$W(u)$ = well function for confined aquifers
$W(u_A, \eta)$ = type A well function
$W(u_B, \eta)$ = type B well function

r = radial distance from the well where drawdown is measured

t = time from initial pumping at which drawdown is measured

S = storativity of the aquifer

Sy = specific yield of the aquifer

b = depth of the aquifer before pumping

k1 = vertical hydraulic conductivity

k2 = horizontal hydraulic conductivity

Values for $W(u)$, $W(u_A,\eta)$ and $W(u_B,\eta)$ can be found in standard hydrology texts or engineering manuals. For $\mu<.01$, $W(u)$ can be approximated as:

$$W(u) = \ln \frac{2.246\ T\ t}{r^2\ S}$$

The previous equations are based on the following assumptions:

- the aquifer is homogeneous,
- the aquifer is not leaky,
- the well penetrates and is screened over the entire depth of the aquifer,
- pumping rate is uniform over time,
- only one aquifer is affected by the well,
- there are no barriers or rivers within the radius of influence of the well, and
- flow to the well remains saturated for confined aquifers.

For a multiple well system total drawdown at a given place and time is simply the added drawdown of each individual well such that (Freeze and Cherry, 1979):

$$s_{total} = \sum_{i=i}^{n} s_{well\ (i)}$$

Wellpoint System

A wellpoint system is used in shallow, unconfined aquifers. It consists of a series of riser pipes screened at the bottom and connected to a common header pipe and a centrifugal pump. A typical wellpoint dewatering system is shown in Figure 3-10.

Wellpoint systems are practical up to 10 meters (33 ft) and most effective at 4.5 meters (15 ft)(Sommerer and Kitchens, 1980). Their effectiveness, however, will depend on site-specific conditions.

Spacing of individual wellpoints also depends on site-specific conditions, particularly the hydraulic conductivity of the aquifer. Wellpoints should be close enough together so that sufficient drawdown is maintained between the wells. Typical spacing is 1 to 2 meters (3 - 7ft)(Sommerer and Kitchens, 1980).

Deep Well Systems

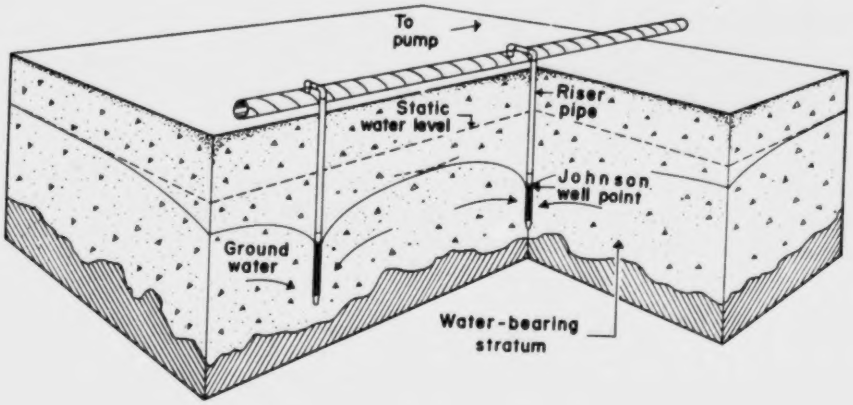
Deep well systems can be used in aquifers located at depths up to several hundred meters.

Construction methods and concerns for deep wells are the same as those for monitoring wells. Wells must be of sufficient diameter (at least 10 cm) to house a submersible pump and handle expected flow (Sommerer and Kitchens, 1980)

Well spacing and location depends on site-specific conditions, particularly the hydraulic conductivity of the aquifer and adjoint soils. Wells should be spaced such that sufficient drawdown is maintained between wells (Sommerer and Kitchens, 1980).

FIGURE 3-10

SCHEMATIC OF A WELL POINT DEWATERING SYSTEM
(Source: EPA, 1982)


To pump
Static water level
Riser pipe
Johnson well point
Ground water
Water-bearing stratum

Special Precautions and Limitations

If any of the assumptions listed below the drawdown equation is not valid for a particular well system, the simple drawdown equations are not valid. A hydrologist should be consulted to determine drawdown on a site-specific basis.

The effect of long-term pumping on local groundwater levels should be considered (Sommerer and Kitchens, 1980). Recharge of the aquifer may be necessary in some cases to maintain water levels or conform with state law.

3.2.5.4 Principal Data Requirements

Depth to impermeable strata (effectiveness of pumping)

Soil characteristics (soil suitability to pumping)

- grain size distribution
- texture

Groundwater characteristics (effectiveness of pumping)

- depth to water table
- potentiometric surfaces - hydraulic gradient
- recharge quantity

Aquifer characteristics (effectiveness of pumping)

- transmissivity
- storativity
- specific yield
- depth
- type - confined or unconfined
- condition- homogeneous, leaky, isotropic
- extent - limited by barriers or surface water

Regulations concerning maintenance of existing water table levels.

3.2.5.5 Elements of Cost Review

Components

Construction and Capital--

- well drilling
- pumps
- casing and screening material
- treatment system or recharge basin

O & M--

- electricity for pump
- pump maintenance
- monitoring

Major Factors

- number and depth of wells
- casing and screening material
- pump size
- drilling techniques
- treatment or recharge

Data

Unit costs for groundwater pumping wells and a recharge basin are given in Table 3-9.

Total cost for an 11 meter (36 ft) deep, 22 well system using 22, 4-inch submersible pumps and 8-inch steel piping in 1982 dollars is $269,000 (EPA, 1982).

3.2.6 Subsurface Drains

3.2.6.1 Description

Subsurface drains are constructed by placing tile or perforated pipe in a trench, surrounding it with a gravel (or similar material) envelope, and backfilling with topsoil or clay. Historically they have been used to dewater agricultural and construction sites. At an uncontrolled site, subsurface drains can be installed to collect leachate as well as lower the water table for site dewatering.

TABLE 3-9
UNIT COSTS FOR WELL INSTALLATION

Unit		1982 $ Cost
Wells:	Construction and installation without casing	2.96 - 3.70 per inch diameter per foot of depth
	Casing	
	4 inch PVC	5.45/ft
	6 inch PVC	7.87/ft
	8 inch PVC	12.71/ft
	4 inch Submersible pump 180 feet; 23gpm	1500
	Steel Pipe (8")	53.64/ft
Recharge Basins:		
	Excavating costs using a backhoe	1.82/yd^3
	Hauling; assume one mile round trip	2.98/yd^3
	Retaining Wall using stone filled gabions	91.96/linear foot
	Sand liner (including transportation costs)	8.47/yd^3

Source: EPA, 1982

3.2.6.2 Status

Conventional, demonstrated

3.2.6.3 Feasibility and Effectiveness

Design Flow

Design flow per meter of drain can be determined by performing a water balance to estimate the amount of water a drain will need to be able to transport (EPA, 1982). Manning's formula can then be used to determine pipe size (Linsley and Franzini, 1979).

Inflow to a pipe can also be roughly estimated as (Frogge and Sanders, 1977):

$$Q = \frac{DA\ (k)}{10}$$

where:

Q = inflow to pipe (m^3/sec)
DA = area drained by pipe (m^2)
k = soil permeability (m/sec)

This should be used as a rule of thumb only.

When a subsurface drainage system involves more than one line of drains, inflow to the drains downgradient of the first line is typically assumed to be 75 percent of that of the first line (Frogge and Sanders, 1977).

Drain Spacing

Distance between adjacent drains is primarily a function of drain depth, design flow (hydraulic capacity) of the drain, and soil permeability. The equation normally used to determine drain spacing is (Linsley and Franzini, 1979):

$$L = \frac{4k\ (b^2 - a^2)}{Q}$$

where:

L = distance between adjacent drains (m)
k = soil permeability (m/sec)
Q = design flow per meter of drain (m^3/sec/m of drain)

a = height of drain above impermeable barrier (m)

b = maximum height of water table above impermeable barrier (m)

See Figure 3-11.

This equation assumes steady-state, one-dimensional flow through homogeneous soil. If these assumptions are not valid, spacing may be determined experimentally based on soil properties. Determining spacing based on two or three dimensional flow becomes a differential boundary value problem based on Laplace's equation. This can be solved using computer generated or published solutions (EPA, 1982).

Drain Depth

Drain depth is determined based on site-specific conditions. In general, the deeper the drain, the wider the spacing that is possible (and, therefore, the fewer drains that are required). However, cost of deeper drains with larger design flow should be compared with shallower drain with smaller design flow to determine the optimal number and depth of drains.

Construction

An envelope of permeable material (typically gravel) should surround the drain pipe. Recommended minimum thickness of the drain envelope is 8 to 10 cm (3 to 4 in.) (EPA, 1982). A typical envelope thickness is 14 cm (6 in.) and can be much larger. For example, at the Love Canal the gravel envelope was about 66 cm thick (26 in.). The envelope of permeable material may be wrapped with a fabric to prevent clogging with soil (EPA, 1982).

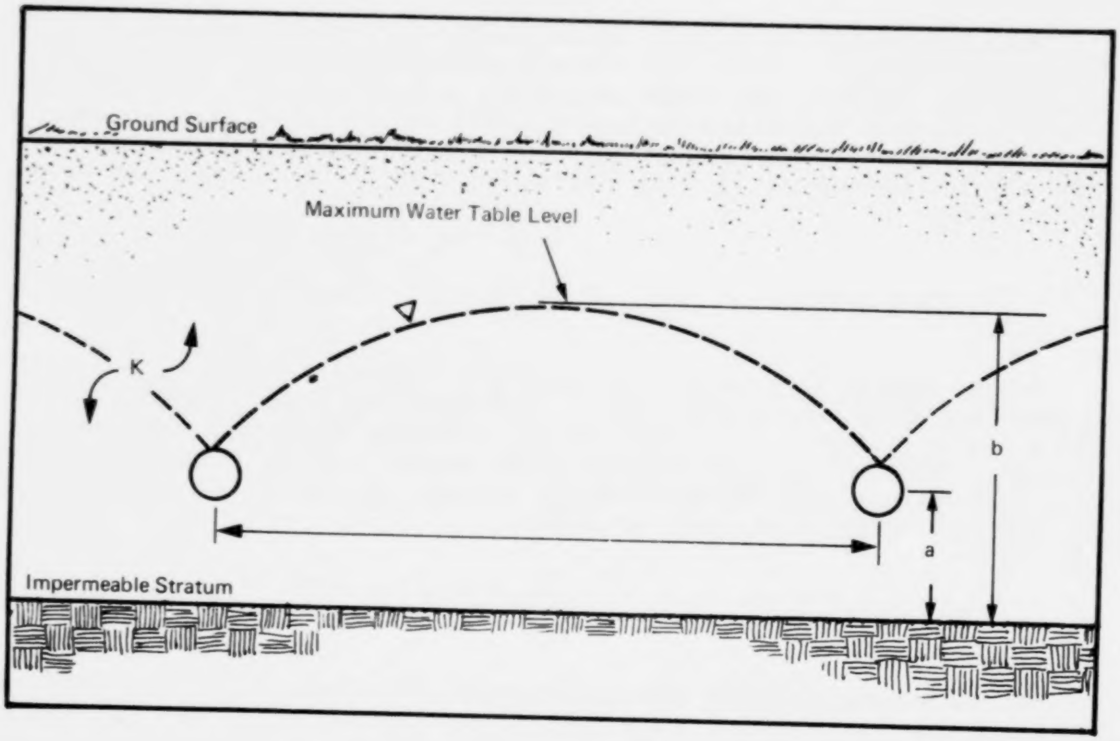
Drain slopes should be sufficient to prevent the settling of suspended solids. Minimum recommended slopes for three pipe diameters are (EPA, 1982):

Diameter (cm)	Grade (%)
10	.10
12.5	.07
15	.05

FIGURE 3-11

SPACING EQUATION DIAGRAM

(After: Frogge and Sanders, 1977)



Manholes should be designed into the system to enable periodic maintenance.

Special Precautions and Limitations

Drain pipes should be designed to withstand loading from equipment, waste and fill material. A minimum drain depth of 1.2 meters (4 ft) is recommended if loading from moving equipment is expected. Design procedures for selecting pipe strength and designing for structural stability are given in TRD 4.

Drain material should be compatible with groundwater and leachate characteristics. In general, fired clay is more suitable for corrosive or high strength chemical wastes than plastic or metal pipe (EPA, 1982).

3.2.6.4 Principal Data Requirements

Depth to impermeable strata (drain spacing)

Soil permeability (drain spacing and pipe inflow)

Depth to water table (drain spacing)

Groundwater and leachate chemistry (pipe material selection)

Drainage area of pipes (inflow to pipe)

3.2.6.5 Elements of Cost Review

Components

Construction and Capital--

- trench excavation
- envelope material
- backfill material
- drain material
- pumps

O & M--

- electricity for pumping
- monitoring and analysis

TABLE 3-10
UNIT COSTS FOR A SUBSURFACE DRAINAGE SYSTEM

Item	1982 Unit Cost
Excavation; 20 ft. deep, 4 ft. wide; hydraulic backhoe	$ 1.27/yd^3
Crushed stone; 3/4 inch Cost to buy, load, haul 2 miles, place, and spread	$ 10.54/yd^3
Tile Drainage	
Vitrified clay (Standard bell and spigot)	
4" perforated	$ 2.73/LF installed
6" perforated	$ 3.34/LF installed
8" perforated	$ 5.50/LF installed
Precast concrete manholes	
48" x 3'	$229.35
48" x 4'	$273.98
Concrete wetwells	$8,300
Sewer piping;	
Concrete; nonreinforced; extra strength	
6" diameter	$ 5.00/LF
8" diameter	$ 5.47/LF
Bituminous fiber	
4" diameter	$ 2.58/LF
Sewer piping; PVC	
4"	$ 2.11/LF
6"	$ 3.50/LF
8"	$ 5.58/LF
Backfilling: Spread dumped material by dozer	$ .84/yd^3

LF = linear foot

TABLE 3-10

UNIT COSTS FOR A SUBSURFACE DRAINAGE SYSTEM (Cont.)

Item	1982 Unit Cost
4" Submersible pumps installed; to 180 ft.	
2 HP; 840-1440GPH	$ 2,100
5 HP; 1302 - 1494 GPH;	$ 2,900
Holding tank; Horizontal cylindrical glass fiber reinforcement phthalic risen tanks	
10,000 gal	$ 7,700 installed
20,000 gal	$ 17,100 installed
Portland cement grout	$ 1.10/gallon
Bentonite grout	$ 1.40/gallon

Source: EPA, 1982

Major Factors

- number, size, and depth of drains
- number and size of pumps

Data

Unit costs for a subsurface drainage system are given in Table 3-10.

Total cost for a drain system 260 meters (850 ft) long and 6 meters (20 ft) deep using 4-inch cement pipe and one submersible pump, in 1982 dollars, is $32,500 to 43,800. O & M accounts for approximately one-third of total costs, primarily due to sample collection and analysis (SCS, 1980).

3.3 SURFACE WATER CONTROL TECHNOLOGIES

3.3.1 Dikes

3.3.1.1 Description

Dikes are compacted earthen ridges designed to divert or retain surface water flow. They can be used to control floodwater or to control runoff.

Flood control dikes (or levees) are divided into three classes. These are described in Table 3-11.

Runoff control dikes are divided into two groups:

- interceptor dikes which are built with a 0% grade and are designed only to reduce slope length; and
- diversion dikes which are built with a grade sufficient to drain and are designed to intercept and divert surface flow as well as reduce slope length.

3.3.1.2 Status

Conventional, demonstrated.

3.3.1.3 Feasibility and Effectiveness(SCS, 1973)

Flood Control Dikes

Information in this part is from SCS 1973, unless otherwise noted.

Height-- Design height, H, of a dike is given by:

TABLE 3-11
DIKE CLASSIFICATION

Class	Site Conditions	Design Requirements
Class I	•Maximum protection against flooding is required •Water levels ≥4 meters above normal ground level are expected	•Design height equals depth of record, 100 year, or 50 year flood, plus wave allowance in excess of 60 cm (2 ft) •Cross section design based on wave action, site exposure and soil stability analysis •Stable mineral soil required in foundation and embankment
Class II	•Moderate protection required •Water levels ≤4 meters above normal ground level are expected	•Design height equals depth of 25 year flood or greater. A less stringent design may be used if fuse plug sections or other relief measures are included in the design •Cross section design based on design water height
Class III	•Minimum protection required •Water levels <2 meters for mineral soils and <1.3 meters for organic soils are expected	•Design based on SCS state standards for specific site condition

Based on Engineering Standards for Dikes - Code 356, SCS, National Engineering Handbook

Source: SCS, 1973

$H = H_w + H_v + H_s$ if $H_v > H_f$; or

$H = H_w + H_f + H_s$ if $H_f > H_v$.

where:

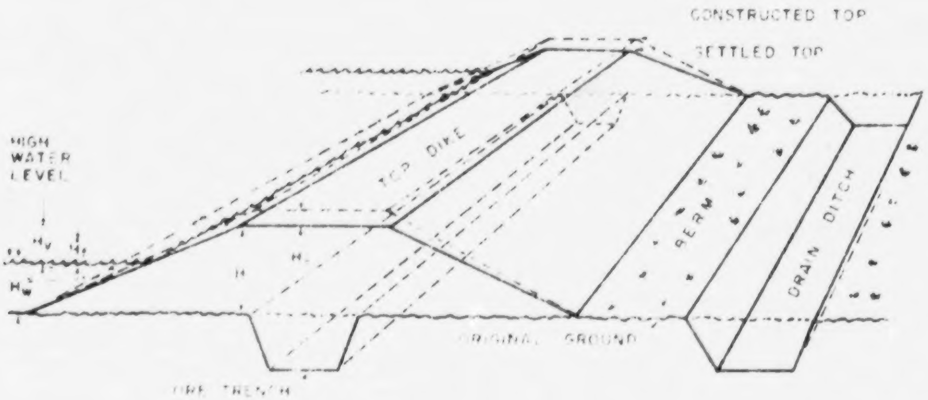
H_w = design high water stage

H_v = additional height for wave action

H_f = additional height for freeboard

The constructed height of a dike is $H + H_s$, where H_s is an allowance for settlement.

FIGURE 3-12
TYPICAL DIKE CROSS SECTION
(Source: SCS, 1973)


CONSTRUCTED TOP
SETTLED TOP
HIGH WATER LEVEL
H_v
H_w
H
TOP DIKE
BERM
DRAIN DITCH
ORIGINAL GROUND
CORE TRENCH

These are shown in Figure 3-12.

Wave height allowance is based on:

- wind velocity and duration,
- fetch;
- angle of wave action,
- Hw, and
- length of dike.

Minimum allowance for freeboard is .6 meters (2 ft).

Settlement allowance depends on:

- dike materials
- construction methods.

General rules of thumb for Hs include:

- $Hs \geq 5\% H$ if dike is compacted by heavy equipment
- $Hs \geq 10\% H$ if dumped fill is placed and shaped
- $Hs \geq 40\% H$ if soil is unusually high in organic matter

Top width-- Recommended top widths are given in Table 3-12.

Side slopes-- Recommended side slopes are given in Table 3-13.

Construction-- Suitability of various soils for use in dike construction is given in Table 3-14. Table 3-14 also indicates which soils may require the construction of core trenches to eliminate seepage under Class I and Class II dikes.

A banquette or constructed berm should protect the land side toe of the dike if the structure crosses an old channel, has excessively porous fill, or has poor foundation conditions. Banquette width should be greater than dike height and should be more than 30 cm (1 ft) above ground level.

Class 1 and II dikes may require foundation and toe drains to control excess seepage and backwater flow.

Dike route should meet the following conditions:

- follow the shortest economically feasible path consistent with protecting the site;
- avoid natural physical hazards, such as sloughs or eroding slopes;

TABLE 3-12
RECOMMENDED DIKE TOP WIDTHS[a]

Class	Dike Height (m)	Soil	Width (m)
I	> 5	Mineral	3.9
I	≤ 5	Mineral	3.3
II, III	> 2	Mineral	2.6
II, III	≤ 2	Mineral	2.0
III	≤ 1.3	Organic	2.6

[a] Equipment width (3.3 meters) required if top is used as a maintanance road

Source: SCS, 1973

- attempt to use natural protection against waves, such as areas of trees or brush;
- border public roads and property lines where possible to allow easy access and property easement; and
- utilize natural storage basins where possible.

Fill material for levees should be taken from borrow pits within the floodplain where possible to provide alternative storage volume for floodwaters.

Runoff Control Dikes (EPA, 1976, Vol. 2)

Design requirements for runoff control dikes may vary according to state regulations. No formal design plan is required for these dikes. Typical requirements are given in Table 3-15.

Spacing of interceptor dikes depends on slope of the area above the dike:

TABLE 3-13
RECOMMENDED DIKE SIDE SLOPES

Dike Description	Maximum Slope
Class I; (stability analysis should be performed to determine exact slope)	4:1
Class II, III; water depths < 2 m, compacted fill	1.5:1
Class II,III; water depths < 2 m, fill not compacted	2:1
Class II,III; water depths 2 to 4 m, compacted fill	2:1
Class II, III; water depths 2 to 4 m, fill not compacted	2.5:1
Soil has low plasticity, or significant wave action or frequent, rapid drawdown is expected	3:1

Source: SCS, 1973

TABLE 3-14
SOIL CHARACTERISTICS

	Group Symbol	Soil Description	Suitability - Dikes	Permeability and Slopes
Coarse-grained soils - (Less than 50% passing #200 sieve)	GW	Well graded gravel and gravel-sand mixtures. Little or no fines.	Very stable - suited for shell of dike. Good foundation bearing.	Rapid - will need core.
	GP	Poorly graded gravels and gravel-sand mixtures. Little or no fines.	Stable - suitable for shell of dike. Good foundation bearing.	Rapid - may not need core for lower stages of short duration.
	GM	Silty gravels and gravel-sand-clay mixtures.	Stable - generally adequate for all stages. Good foundation bearing. Good compaction with rubber tires.	Moderate - may not need core except for long flood duration.
	GC	Clayey gravels and gravel-sand-clay mixtures.	Stable - adequate for all stages. Good foundation bearing. Good compaction with rubber tires.	Slow permeability
	SW	Well graded sands and gravelly sands. Little or no fines.	Very stable - adequate for low stages. Good foundation bearing. Compaction good with crawler tractor.	Rapid - may need core for high stages of long duration.
	SP	Poorly graded sands and gravelly sands. Little or no fines.	Stable - adequate for low stages. Generally fair foundation bearing. Use flat slopes and wide berms. Compaction good with crawler tractor.	Rapid - will need core for long duration. Use flat slopes. Protect against wave action.
	SM	Silty sands and sand-silt mixtures.	Fairly stable - adequate for low stages. Only fair foundation bearing. Use wide berms. Good compaction with rubber tires.	Moderate - use flat slope on water side. Protect against wave action.
	SC	Clayey sands and sand-clay mixtures	Stable - adequate for all stages. Generally good foundation bearing. Fair compaction with rubber tires.	Slow -

TABLE 3-14
SOIL CHARACTERISTICS (Cont.)

	Group Symbol	Soil Description	Suitability - Dikes	Permeability and Slopes
Fine-grained soils - (More than 50% passing #200 sieve)	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands and clayey silts of slight plasticity.	Poor stability - generally adequate for low stages. Fair foundation bearing. Dumped fill on Class III dikes only. Fair compaction with rubber tires.	Moderate - use flat slope on water side. Protect slopes against erosion forces.
	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays and lean clays.	Stable - adequate for all stages. Fair foundation bearing. Fair compaction with rubber tires. Use dumped fill on lower stages only.	Slow -
	OL	Organic silts and organic clays having low plasticity.	Very poor stability - may be adequate for Class III dikes of low height. Can use dumped fill.	Moderate - use for very low stage only. Slopes at natural angle of repose when wet.
	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils and elastic silts.	Low stability - generally adequate for all stages. Difficult to compact. Could use dumped fill for low stages. Poor foundation bearing.	Slow - use flat slopes and protect against erosion.
	CH	Inorganic clays having high plasticity and fat clays.	Fairly stable - adequate for all stages. Poor compaction, dumped fill may be adequate.	Very slow permeability. Use flat slopes on water side.
	OH	Organic clays having medium to high plasticity and organic silts.	Very low stability - Adequate only for low stages and can use dumped fill. Has poor foundation bearing and compaction.	Very slow - use for low stages only. Use flat slopes.
	Pt	Peat and other highly organic soils.	Very low stability - use only for temporary dikes. Remove from foundation for mineral soil dikes.	Variable - may vary significantly between vertical and horizontal.

Note: This table based on the Unified Classification System and field experience. Rubber tires refer to rubber tired equipment.

Source: SCS, 1973

TABLE 3-15
RUNOFF DIKE REQUIREMENTS

Parameter	Typical Requirement	Comments
Height	.45 meters minimum	9 cm freeboard required if used as a diversion
Top width	.6 meters minimum	1.2 meters if used as a diversion
Side slope	2:1 (50%) or flatter	
Drainage area	$2x10^4 m^2$ (5 acre) maximum	
Design life	1 year	Can be extended if stabilized and well maintained
Grade	Should be positive	
Stabilization	Required if slope is over 5%	

Source: EPA, 1976 Vol. 2

Slope	Distance Between Dikes
>10%	45m (150 ft)
5-10%	60m (200 ft)
< 5%	90m (300 ft)

Special Precautions and Limitations

None.

3.3.1.4 Principal Data Requirements

Flood Control Dikes

Topography (construction and route)

Accessibility of suitable construction material (cost, implementability)

Depth to low-permeability stratum or bedrock (depth of subsurface cutoff)

Soil characteristics (construction and dike stability)

- organic content
- strength properties
- erosion potential (see discussion of erosion control in Section 2)

Wind characteristics (dike height)

- velocity
- duration

Flood characteristics (dike height, class required)

- height of design flood
- wave angle and fetch
- limits of flood stages
- duration

Runoff Control Dikes

Topography (dike placement)

Soil erosion potential (dike placement and stability) (see discussion of erosion control in Section 2)

Storm characteristics (dike stability, lifetime)

Runoff quantity and depth (dike height, stability)

Drainage area (dike placement, number required)

State regulation (design requirements)

3.3.1.5 Elements of Cost Review

Components

Construction and Capital--

- soil required
- impermeable core and cutoff
- equipment
- transportation
- drainage

O & M--

- Maintenance

Major Factors

- dike purpose (flood or runoff control, class)
- number, size and length of dikes
- equipment and material required

Data

Unit costs associated with dikes are given in Table 3-16.

3.3.2 Terraces

3.3.2.1 Description

Terraces are embankments or combinations of embankments and

TABLE 3-16
UNIT COSTS ASSOCIATED WITH SURFACE WATER DIVERSION AND COLLECTION STRUCTURES

Unit Operation	1982 Unit Cost
Excavation, hauling, grading (spreading and compaction)	
1,000 - 5,000 haul	\$ 1.13 - 2.52/yd^3
2 miles	\$ 2.16 - 2.47/yd^3
Grading site excavation and fill (no compaction)	
75 h.p. dozer 300' haul	\$ 2.78/yd^3
300 h.p. dozer 300' haul	\$ 1.85/yd^3
Trench Excavation	
clay hauling spreading compaction	\$ 9.89/yd^3
sand hauling spreading compaction	\$ 17.51/yd^3
Loam, sand and loose gravel	
1' - 6' deep; ½:1 sides	\$ .50 - .85/yd^3
6' - 10' deep	\$ .50 - .66/yd^3
Compacted gravel and till	
1' - 6' deep; ½:1 sides	\$ .50 - .88/yd^3
6' - 10' deep	\$ .38 - .62/yd^3
Building embankments; spreading, shaping, compacting;	
material delivered by scraper	\$ .24 - .48/yd^3
material delivered by back dump	\$ .57 - .80/yd^3
Placement of ditch liner pipe; 1/3 section	
15" radius	\$ 12.19/ft
18" radius	\$ 18.67/ft
24" radius	\$ 23.37/ft
Loose gravel, excavate, load, haul 5 miles spread, compact	\$ 5.15 - 5.67/yd^3
Stone riprap; dumped from trucks, machine placed	\$ 21.12/yd^3

TABLE 3-16
UNIT COSTS ASSOCIATED WITH SURFACE WATER DIVERSION AND COLLECTION STRUCTURES (Cont.)

Unit Operation	1982 Unit Cost
Soil testing	
liquid and plastic	\$44.50/test
hydrometer analysis; specific gravity	\$76.28/test
moisture content	\$10.59/test
permeability	\$63.57/test
proctor compaction	\$50.85 - 57.21/test
shear tests, trioxical	\$243 - 444/test
direct shear	\$90.00 - 286/test
Level spreader construction	\$ 4.53 - 9.06/ft
Corrugated galvanized steel underdrain pipe, asphalt-coated, perforated;	
12" diameter, 16 gage	\$15.24
18" diameter, 16 gage	\$21.59
Corrugated galvanized metal pipe, with paved invert;	
18" diameter, 14 gage	\$25.08/ft
36" diameter, 12 gage	\$63.55/ft
48" diameter, 12 gage	\$84.84/ft
Steel sheet piling;	
15' deep, 22 psf	\$10.35/ft^2
20' deep, 27 psf	\$12.07/ft^2
25' deep, 38 psf	\$15.49/ft^2
Backflow preventer; gate valves, automatic operation, flanged;	
10" diameter	\$11.30 each
Sump pumps;	
6" - 12" centrifugal pumps, operating 1 shift/day	\$229 - 332/day

TABLE 3-16

UNIT COSTS ASSOCIATED WITH SURFACE WATER DIVERSION AND COLLECTION STRUCTURES (Cont.)

Unit Operation	1982 Unit Cost
Temporary sediment basin construction;	
drainage area, 1-25 acres	\$ 560 - 3,020 each
50-75 acres	\$ 5,670 - 9,450 each
75-100 acres	\$ 9,450 - 12,100 each
100-125 acres	\$12,100 - 15,120 each
Sediment removal from basins	\$ 5.67 - 13.23/yd^3
Paved flume, installed	\$ 37.80 - 56.70yd^2

Source: EPA, 1982

channels constructed across a slope (EPA, 1976, Vol. 1). As seen in Figure 3-13, a variety of terrace cross sections are possible depending on slope and site-specific requirements. Terraces can be used to:

- intercept and divert surface flow away from a site; and
- control erosion by reducing slope length.

3.3.2.2 Status

Conventional, demonstrated.

3.3.2.3 Feasibility and Effectiveness

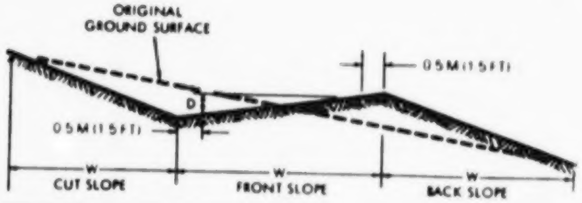
Spacing

If data are sufficient, slope length can be determined using the universal soil loss equation. The equation is (TRD 8):

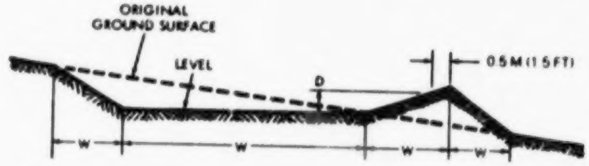
FIGURE 3-13

TYPICAL TERRACE CROSS SECTIONS

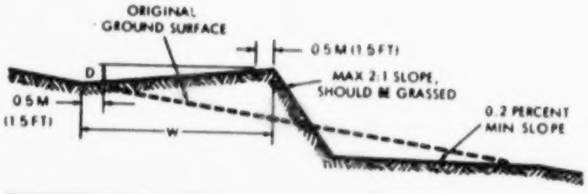
(Source: ASAE, 1978)
Used by permission, see Copyright Notice


ORIGINAL GROUND SURFACE
0.5 M (1.5 FT)
D
0.5 M (1.5 FT)
W
CUT SLOPE
W
FRONT SLOPE
W
BACK SLOPE

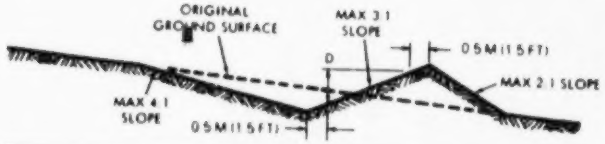
BROADBASE TERRACE CROSS SECTION


ORIGINAL GROUND SURFACE
LEVEL
D
0.5 M (1.5 FT)
W
W
W
W

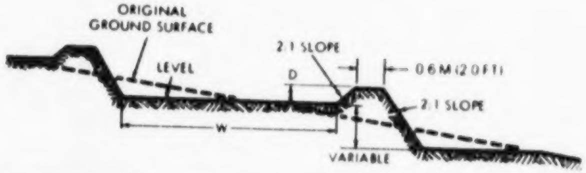
FLAT CHANNEL TERRACE OR ZINGG CONSERVATION BENCH TERRACE CROSS SECTION


ORIGINAL GROUND SURFACE
0.5 M (1.5 FT)
D
MAX 2:1 SLOPE, SHOULD BE GRASSED
0.5 M (1.5 FT)
W
0.2 PERCENT MIN SLOPE

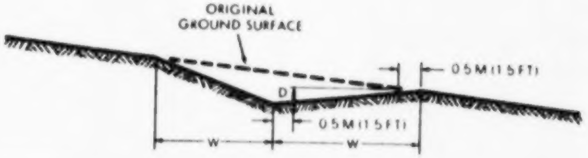
STEEP-BACKSLOPE TERRACE CROSS SECTION


ORIGINAL GROUND SURFACE
MAX 3:1 SLOPE
D
0.5 M (1.5 FT)
MAX 2:1 SLOPE
MAX 4:1 SLOPE
0.5 M (1.5 FT)

NARROW-BASE TERRACE CROSS SECTION. Slopes are the maximum allowable and should be grassed.


ORIGINAL GROUND SURFACE
LEVEL
2:1 SLOPE
D
0.6 M (2.0 FT)
2:1 SLOPE
W
VARIABLE

BENCH TERRACE CROSS SECTION


ORIGINAL GROUND SURFACE
0.5 M (1.5 FT)
D
0.5 M (1.5 FT)
W
W

RIDGELESS CHANNEL TERRACE CROSS SECTION

$$A = RKLSCP$$

where:

A = maximum allowable soil loss
R = rainfall and runoff erosivity index
K = soil erodibility factor
L = slope length
S = slope steepness
C = cover/management factor
P = practice factor

Solving for SL, the horizontal interval (HI) between terraces is found by (SCS, 1973)

$$HI = \left(\frac{100SL}{0.76 + 0.53S' + 0.076S'^2} \right)^2$$

Where: S' is the land slope in percent

The Universal Soil Loss Equation is discussed in detail in TRD 8.

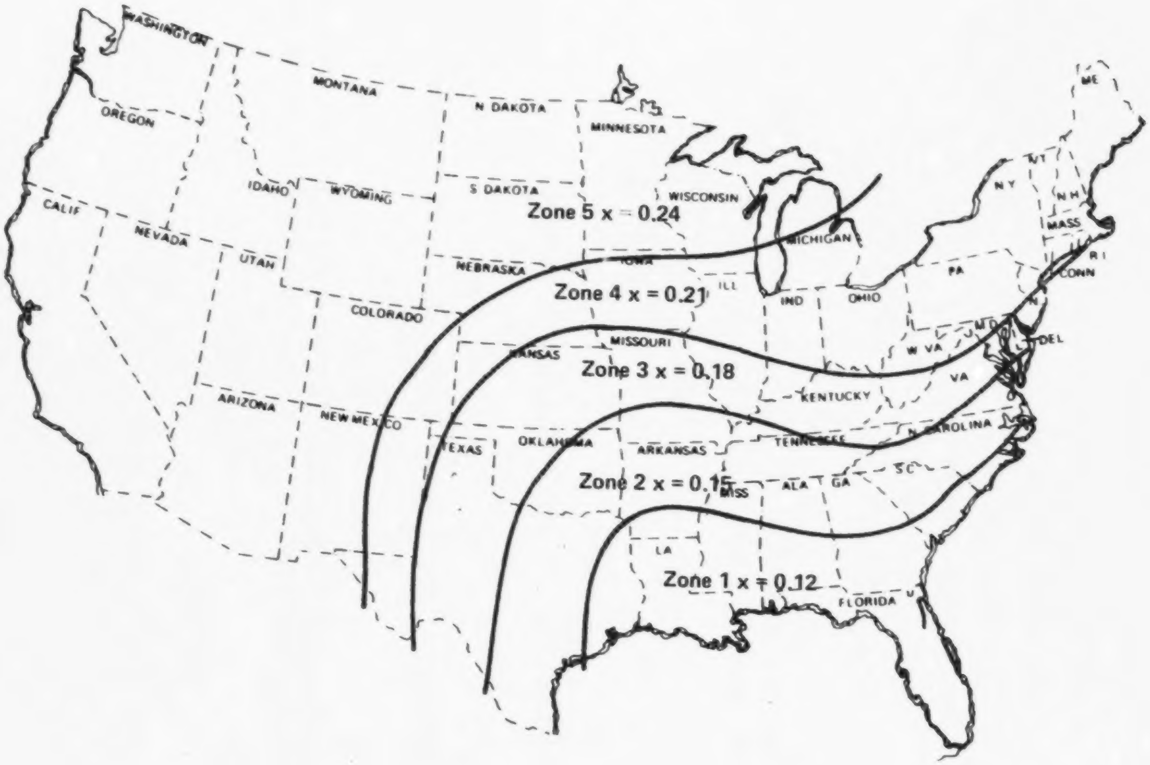
Alternatively, the allowable vertical distance between adjacent terraces, called the vertical interval (VI), is given by (ASAE, 1978):

$$VI = XS + Y$$

where:

VI = vertical interval in meters
X = geographic constant given in Figure 3-14
S = average slope of the land draining on to the terrace

FIGURE 3-14
VALUES OF X IN EQUATION VI = XS+Y
(Source: Sommerer and Kitchens, 1980)


WASHINGTON
MONTANA
N DAKOTA
MINNESOTA
ME
OREGON
IDAHO
WYOMING
S DAKOTA
WISCONSIN
N Y
VT
N H
MASS
R I
CONN
CALIF
NEVADA
UTAH
Zone 5 x = 0.24
MICHIGAN
NEBRASKA
IOWA
PA
N J
Zone 4 x = 0.21
ILL
IND
OHIO
COLORADO
MD
DEL
KANSAS
MISSOURI
W VA
Zone 3 x = 0.18
VA
KENTUCKY
ARIZONA
NEW MEXICO
N CAROLINA
TEXAS
OKLAHOMA
ARKANSAS
TENNESSEE
S C
Zone 2 x = 0.15
MISS
ALA
GA
LA
Zone 1 x = 0.12
FLORIDA

Y = constant valued at .3, .6, .9, or 1.2 based on soil erodibility and land use. Low values of y are appropriate for very erodible soils, and high values for erosion resistant soils.

This provides an estimate that can be varied up to 25 percent in the field without serious danger of failure (TRD 8).

Cross Section

Terrace cross section dimensions (width = w, and height = h), are a function of capacity, slope, length, roughness coefficient (Manning's n) and soil erodibility. Combining Manning's formula and the flow equation:

$$Ar^{2/3} = \frac{Qn}{C_m S^{1/2}}$$

where:

Q = design capacity (m^3/sec.) Usually the peak runoff is from the 24-hour, 10-year frequency storm (Rochester and Busch,1974). However, larger capacities may be required depending on the consequences of terraces failure.

n = Manning roughness coefficient. ASAE recommends using .06 as an estimated value.

Cm = dimensionless. (1.0 when using metric units)

S = slope or terrace grade (m/m). Depends on terrace length and soil erodibility. Maximum grades are given in Table 3-17.

A = cross-section area.

r = hydraulic radius (area divided by wetted perimeter, (w x h)/(w + 2h), in m).

TABLE 3-17
MAXIMUM TERRACE GRADES

Terrace length (m) or length from upper end of long terraces	Slope (per cent)	
	Erosive soil (Silt loam)	Resistant soil (Gravelly or Rocky)
153 or more	0.35	0.50
153 or less	0.50	0.65
61 or less	1.00	1.50
31 or less	2.00	2.50

Source: TRD 8

Determination of the relationship between height and width depends on slope and other site-specific conditions. Height should allow for settlement, channel sediment deposits, ridge erosion, and a safety factor. Ridge and channel should have a minimum, total width of 0.9 meters (3 ft) (ASAE, 1978).

There are no general rules for determing type of cross section used. However, as field slope increases, ridge height (or channel depth), terrace width and grade should also increase. Some details, particular to a given cross section, are shown in Figure 3-13.

Length

Maximumm recommended terrace length is 300 to 350 meters (980 to 1,150 ft) (TRD 8).

Drainage

Terraces should be designed so that they drain in a maximum of 48 hours.

Graded or open-ended terraces use vegetated outlets. Closed-end or level terraces use underground outlets (underground conduit with outlet pipe) or soil infiltration.

Special Precautions and Limitations

None.

3.3.2.4 Principal Data Requirements

Topography (spacing and cross section dimensions)

Vegetation (land use, spacing)

Soil erosion potential (spacing, stability)

Infiltration rate (drainage)

Runoff (cross section dimensions)

3.3.2.5 Elements of Cost Review

Components

Construction and Capital--

- equipment
- additional material
- transportation

O & M--

- Maintenance

Major Factors

- number, size and length of terraces

- material and equipment availability

Data

Unit costs associated with terraces are given in Table 3-16.

3.3.3 Channels

3.3.3.1 Description

Channels are excavated ditches that are generally wide and shallow with trapezoidal, triangular, or parabolic cross sections. Diversion channels are used primarily to intercept runoff or reduce slope length. They may or may not be stabilized. Channels stabilized with vegetation or stone riprap (waterways) are used to collect and transfer diverted water off site or to on-site storage or treatment.

3.3.3.2 Status

Conventional, demonstrated.

3.3.3.3 Feasibility and Effectiveness

Design Flow

The Manning formula is considered when designing for steady uniform flow in open channels:

$$V = \frac{Cm}{n} R^{2/3} S^{1/2}$$

and for an open channel of cross-sectional area, A:

$$Q = \frac{Cm}{n} A R^{2/3} S^{1/2}$$

where:

Q = design capacity, m^3/sec
R = hydraulic radius (area divided by wetted perimeter), m
A = cross-sectional area of the channel, m^2
S = channel slope, m/m
Cm = dimensionless constant (1.0 for metric units)
n = Manning roughness factor, $sec/m^{1/3}$. Values of n for various materials are given in Table 3-18

Permissible flow velocities for channels lined with vegetation are given in Table 3-19.

Channel Dimensions

Parabolic cross sections are considered most suitable for use at disposal sites since they cause the least amount of erosion (TRD 8). Typical channel cross sections are shown in Figure 3-15.

Wetted perimeter (p) for a parabolic channel is given by (TRD 8):

$$p = t + \frac{8d^2}{3t}$$

Design requirements for diversion channels may vary according to state regulations. Typical requirements are given in Table 3-20.

Channel spacing (when used for interception or to reduce slope length) depends on the slope of the area above the channel (EPA, 1976 Vol. 2).

Slope	Distance Between Channels
>10%	30m (100 ft)
5-10%	60m (200 ft)
<5%	90m (300 ft)

TABLE 3-18
VALUES OF MANNING'S n FOR VARIOUS CHANNEL SURFACE MATERIALS

Material	Suggested n [a,b]
Planed wood	0.012
Unplaned wood	0.013
Finished concrete	0.012
Unfinished concrete	0.014
Cast iron	0.015
Brick	0.016
Riveted steel	0.018
Corrugated metal	0.022
Rubble	0.025
Earth	0.025
Earth with stones or weeds	0.035
Gravel	0.029
Vegetation	.04 [c]

[a] The Manning formula is an empirical formula. The dimensions of Cm and n are therefore somewhat arbitrary. In metric units, Cm = 1.0 and n is in $(s)/(m^{1/3})$. In English units, Cm = 1.486 $(ft^{1/2})/(s)$ and n is in $ft^{1/6}$. The numerical values for n, however, do not change.

[b] In situations with R>3m, roughness factor should be increased by 10 to 15%.

[c] From TRD 8.

Source: Streeter and Wylie, 1975

TABLE 3-19
PERMISSIBLE VELOCITIES FOR CHANNELS LINED WITH VEGETATION

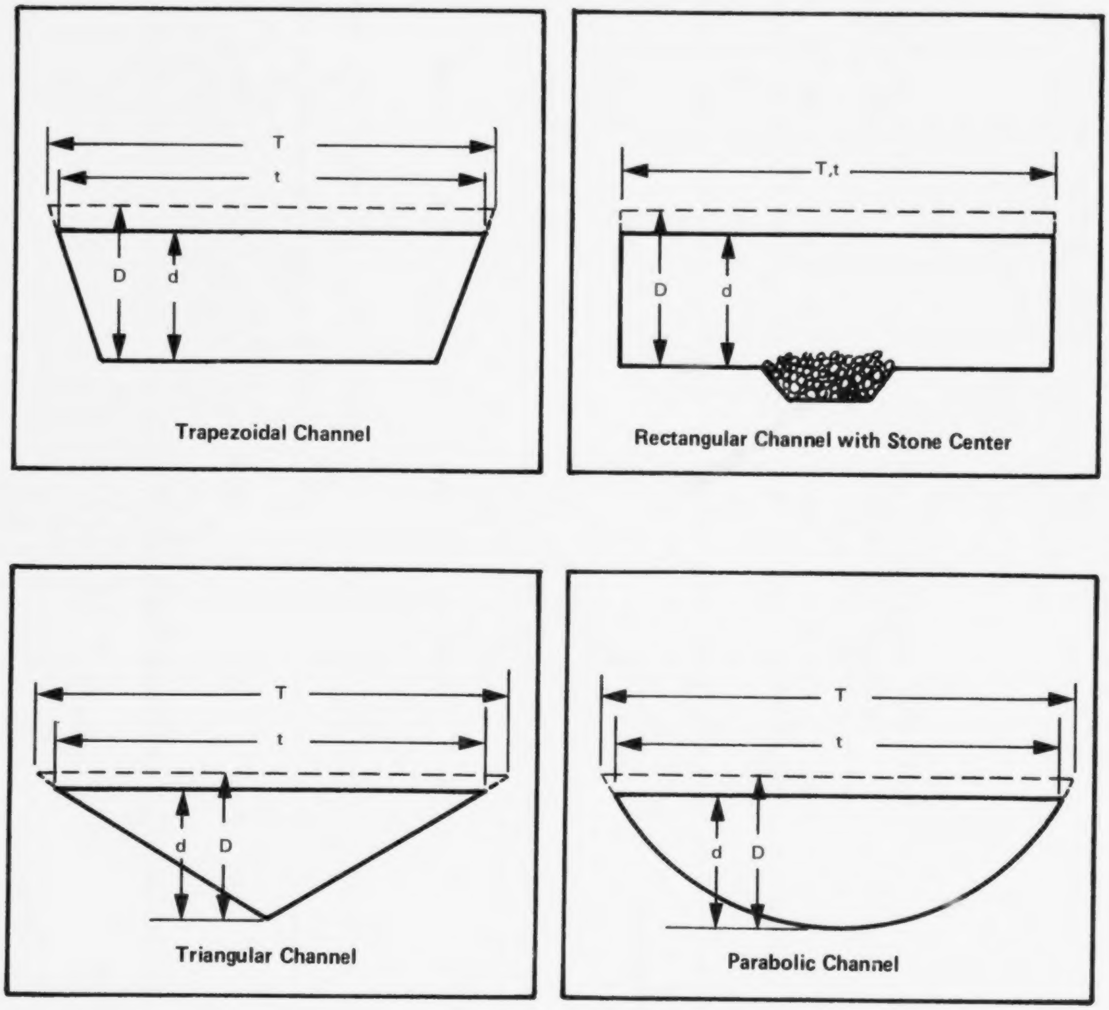
	Permissible Velocity (feet/sec)					
	Erosion resistant soils (per cent slope)			Easily eroded soils (per cent slope)		
Cover	0-5	5-10	Over 10	0-5	5-10	Over 10
Bermuda grass	8	7	6	6	5	4
Buffalo grass **Kentucky bluegrass** **Smooth brome** **Blue grama** **Tall fescue**	7	6	5	5	4	3
Lespedeza serica **Weeping lovegrass** **Kudzu** **Alfalfa** **Crabgrass**	3.5	NR[a]	NR	2.5	NR	NR
Grass mixture	5	4	NR	4	3	NR
Annuals for temporary protection	3.5	NR	NR	2.5	NR	NR

[a] Not Recommended

Source: TRD 8

FIGURE 3-15

TYPICAL CHANNEL CROSS SECTIONS
(After: TRD #8)


T
t
D
d
Trapezoidal Channel
T,t
D
d
Rectangular Channel with Stone Center
T
t
d
D
Triangular Channel
T
t
d
D
Parabolic Channel

Legend:

T = Total Construction Top Width
t = Design Top Width of Water Flow
D = Total Construction Depth
d = Design Depth of Flow

TABLE 3-20
TYPICAL CHANNEL DESIGN REQUIREMENTS

Parameter	Typical Requirement
Depth	.3 meters (1 foot) minimum
Bottom width	2 meters (7 feet) minimum
Side slope	2:1 (50%) or flatter
Drainage area	$2x10^4m^2$ (5 acres) maximum

Source: EPA, 1976

Special Precautions and Limitations

For diversion channels, stabilization with vegetation or stone riprap is required for slopes greater than 5 percent and may be necessary for slopes less than 5 percent, depending on site-specific conditions (EPA, 1976, Vol. 2).

For channels used as waterways, stabilization is required. If flow is expected to be continuous i.e., if there is a base flow, the waterway should have a stone center, as shown in Figure 3-15.

3.3.3.4 Principal Data Requirements

Topography (capacity, placement, stabilization)

Soil erosion potential (stabilization required)

Storm characteristics (stability, lifetime)

Drainage area (placement)

State regulations (design requirements)

3.3.3.5 Elements of Cost Review

Components

Construction and Capital--

- channel excavation
- stabilization

O & M--

- Maintenance

Major Factors

- number, size and length of channels
- stabilization required.

Data

Unit costs associated with channels are given in Table 3-16.

3.3.4 Chutes and Downpipes

3.3.4.1 Description

Chutes (or flumes) are open channels normally lined with bituminous concrete, Portland cement, concrete, grouted riprap, or similar nonerodible material.

Downpipes (or downdrains) are drainage pipes constructed of rigid piping (such as corrugated metal) or flexible tubing of heavy duty fabric. They are installed with prefabricated entrance sections. Downpipes can also be open structures constructed by joining half sections of bituminous fiber or concrete pipe.

Chutes and downpipes are useful in transferring concentrated flows of surface runoff from one level of a site to a lower level without erosive damage. Downpipes generally extend downslope from earthen embankments and convey water to stabilized waterways or outlets located at the base of the slope. They are particularly useful in emergency situations since they can be quickly constructed during severe storms to handle excess flow when downslope waterways overflow and threaten the containment of hazardous waste (EPA, 1982).

3.3.4.2 Status

Conventional, demonstrated.

3.3.4.3 Feasibility and Effectiveness

Chutes

Typical design considerations for chutes are given in Figure 3-16.

Chute linings should be well-compacted and smooth, it should be placed by beginning at the lower end and proceeding upslope.

Chutes should be placed on undistributed soil or well-compacted fill.

Bottom width and drainage area are based on chute size group as given in Table 3-21.

Downpipes

Typical design considerations for downpipes are given in Figure 3-17.

Drainage area based on pipe diameter is given in Table 3-22.

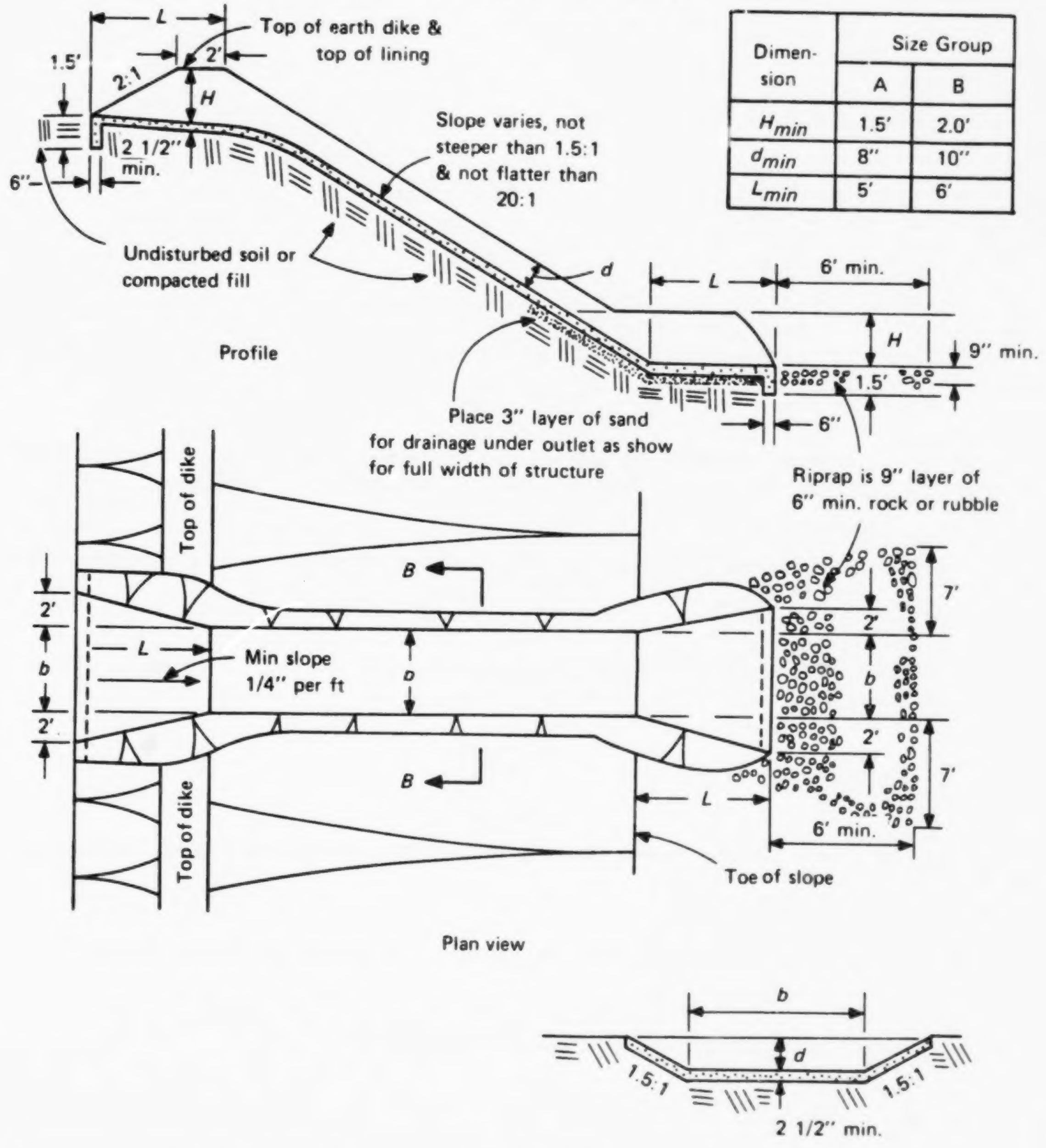
Special Precautions and Limitations

None.

FIGURE 3-16

PAVED CHUTE[a]

(Source: EPA, 1976, Vol. 2)



Dimension	Size Group	
	A	B
H_{min}	1.5′	2.0′
d_{min}	8″	10″
L_{min}	5′	6′

L
Top of earth dike & top of lining
1.5′
2:1
2′
H
2 1/2″ min.
6″
Slope varies, not steeper than 1.5:1 & not flatter than 20:1
Undisturbed soil or compacted fill
d
L
6′ min.
H
9″ min.
1.5′
6″
Profile
Place 3″ layer of sand for drainage under outlet as show for full width of structure
Riprap is 9″ layer of 6″ min. rock or rubble
Top of dike
B
2′
L
Min slope 1/4″ per ft
b
b
2′
7′
2′
b
2′
7′
B
L
6′ min.
Top of dike
Toe of slope
Plan view
b
d
1.5:1
1.5:1
2 1/2″ min.
Section B-B.

---

[a] Requirements for chute designs vary according to state regulations. Values given are typical.

TABLE 3-21

CHUTE BOTTOM WIDTH AND DRAINAGE AREA

Size Group [a]	Bottom Width b, m meters (feet)	Maximum Drainage Area (x $10^4 m^2$) [b] Units (acres)
A-2	.07 (2 ft)	2.0 (5 acres)
A-4	.14 (4)	3.2 (8)
B-4	.14 (4)	5.7 (14)
A-6	.21 (6)	4.4 (11)
B-6	.21 (6)	8.1 (20)
A-8	.28 (8)	5.7 (14)
B-8	.28 (8)	10.1 (25)
A-10	.35 (10)	7.3 (18)
B-10	.35 (10)	12.5 (31)
B-12	.42 (12)	14.6 (36)

[a] For size group characteristics, see Figure 3-15.

[b] If 75% of drainage area has good vegetative cover (established grasses and/or shrubs) throughout the design life of the chute, maximum drainage area may be increased by 50%.

If 75% has a mulch cover throughout the structure's life, maximum drainage area may be increased by 25%.

Source: After EPA, 1976, Vol. 2

3.3.4.4 Principal Data Requirements

Topography (placement)

Soil erosion potential (placement)

Storm characteristics (capacity)

Runoff (capacity)

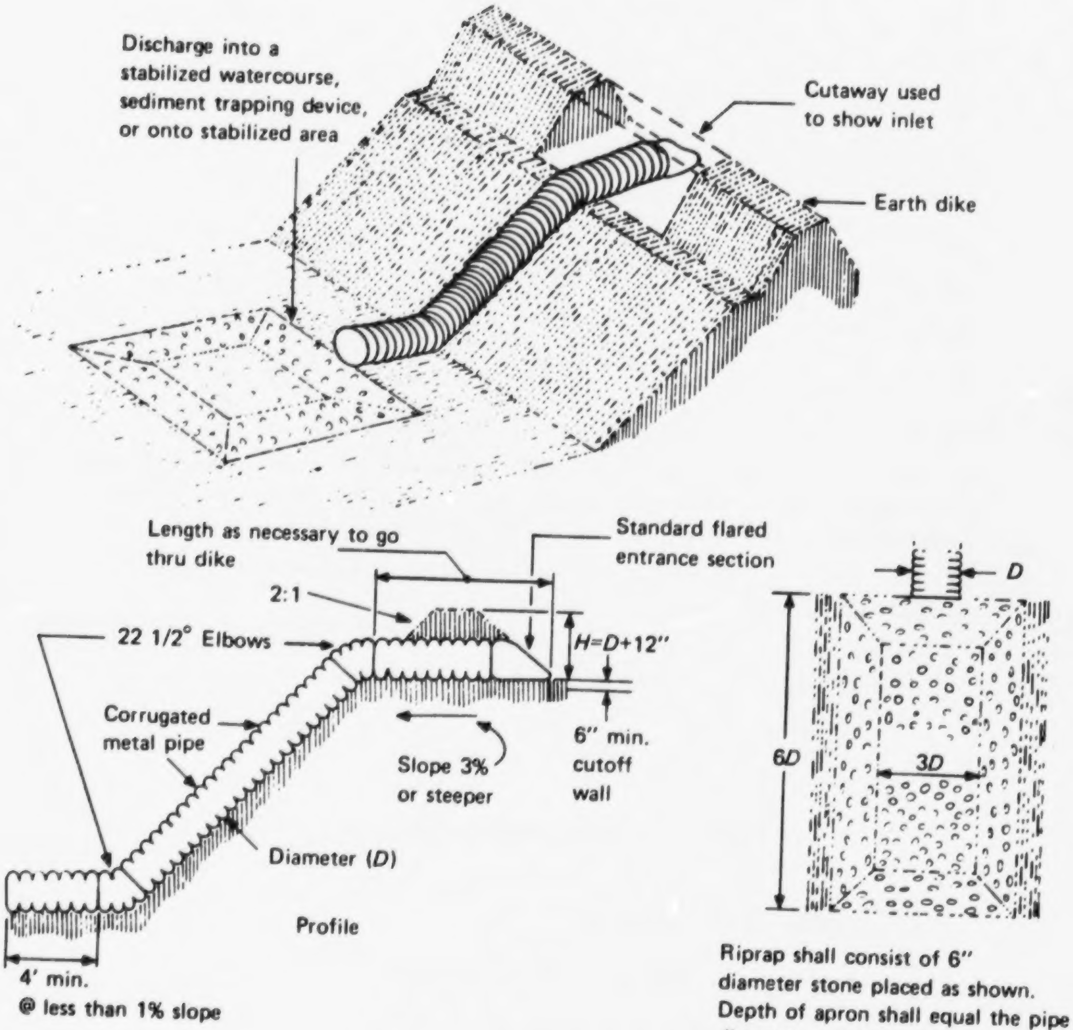
Drainage area (capacity)

State regulations (design requirements)

FIGURE 3-17

DOWNPIPE[a]

(Source: EPA, 1976. Vol. 2)


Discharge into a stabilized watercourse, sediment trapping device, or onto stabilized area
Cutaway used to show inlet
Earth dike
Length as necessary to go thru dike
Standard flared entrance section
2:1
22 1/2° Elbows
H=D+12"
Corrugated metal pipe
6" min. cutoff wall
Slope 3% or steeper
Diameter (D)
4' min. @ less than 1% slope
D
6D
3D

Profile

Riprap shall consist of 6" diameter stone placed as shown. Depth of apron shall equal the pipe diameter and riprap shall be a minimum of 12" in thickness.

Riprap apron plan

---

[a] Requirements for downpipe design vary according to state regulations. Values given are typical.

TABLE 3-22
DOWNPIPE DIAMETER AND DRAINAGE AREA

Pipe Diameter meters (inches)	Maximum Drainage Area ($x10^4m^2$) Hectares (acres)	
.31m (12 inches)	.2 hectares	(.5 acres)
.46 (18)	.6	(1.5)
.53 (21)	1.0	(2.5)
.61 (24)	1.4	(3.5)
.76 (30)	2.0	(5.0)

Source: EPA, 1976, Vol. 2

3.3.4.5 Elements of Cost Review

Components

Construction and Capital--

- Channel lining material
- pipe section
- entrance and outlet sections

O & M--

- Inspection and maintenance

Major Factors

- length and size of chute or drainpipe
- construction difficulties.

Data

Unit costs associated with chutes and downpipes are given in Table 3-16.

3.3.5 Grading

3.3.5.1 Description

Grading is the general term for technologies used to modify the natural topography and runoff characteristics of a waste site. Grading primarily involves the use of heavy equipment (such as dozers, loaders, scrapers and compactors) to spread and compact loose soil, roughen and loosen compacted soil, and modify the surface gradient. There are six basic grading techniques described in Table 3-23.

3.3.5.2 Status

Conventional, demonstrated.

3.3.5.3 Feasibility and Effectiveness

Applicability

Grading has two primary applications:

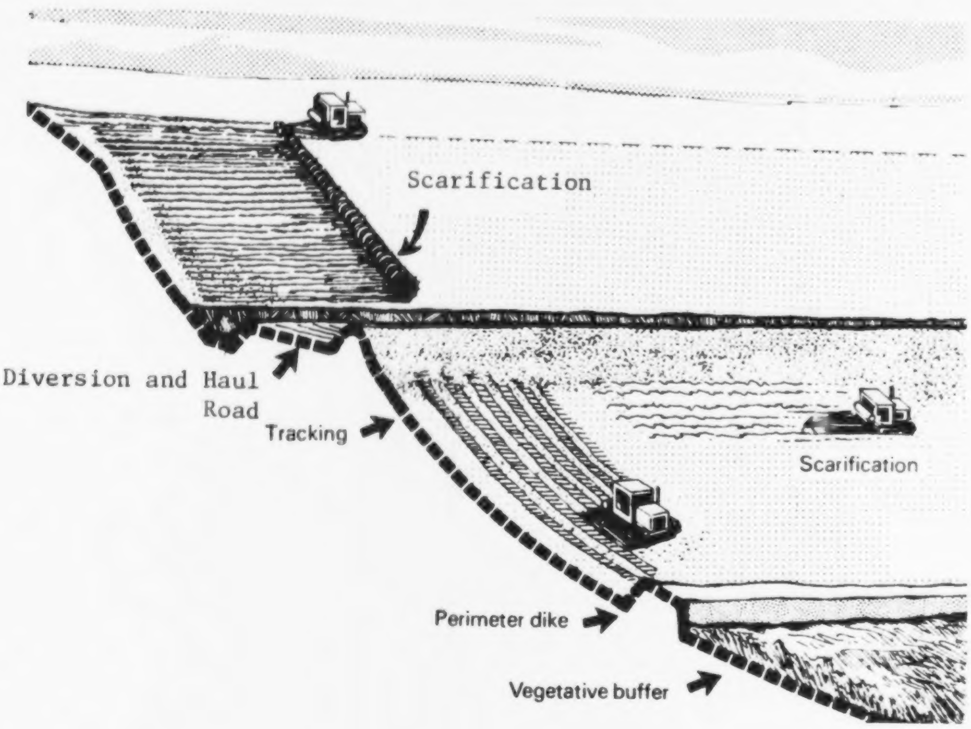
1. Slope grade construction. Excavation, spreading, compaction, and hauling are used to optimize the slope at a waste site such that surface runoff increases and infiltration and ponding decrease without significantly increasing erosion. This is of primary importance in the construction of surface seals and other waste covers.
2. Preparation for revegetation. Roughening techniques (scarification, tracking and contour furrowing) are used to reduce runoff, thereby increasing infiltration, and make the soil receptive to seed or seedlings. This is an important aspect of on-site revegetation once an effective surface seal has been applied. These techniques can also be used off site in conjunction with surface water diversion technologies to control runon, as seen in Figure 3-18.

TABLE 3-23
GRADING TECHNIQUES

Technique	Description	Use	Equipment
Excavation	soil removal	slope grade construction	dozer, loader, scraper
Spreading	soil application smoothing	slope grade construction	dozer, loader, grader
Compaction	compacts soil increases density	slope grade construction	dozer, loader, compactor
Scarification	roughening technique loosens soil	preparation for revegetation increases infiltration	dozer, tractor, harrow
Tracking	roughening technique grooves soil along contour	preparation for revegetation increases infiltration	cleated crawler tractor
Contour Furrowing	roughening technique creates small depressions in soil along contour	preparation for revegetation increases infiltration	dozer

FIGURE 3-18

SURFACE WATER CONTROLS UPSLOPE OF WASTE SITE
(Source: EPA, 1976, Vol. 1)


Scarification
Diversion and Haul Road
Tracking
Scarification
Perimeter dike
Vegetative buffer

Compaction

Compaction is one of the most important grading technique. Compaction can be accomplished by (Marek, 1977):

- rolling,
- impact with heavy object,
- vibration, and
- loading with static weight.

Characteristics of various types of compaction equipment are given in Table 3-24.

Degree of compaction can be determined by taking a soil sample, drying it, and filling the hole with sand of known density by the following equations (Marek, 1977):

$$V = Ws/Ds$$

$$M = \frac{100\ (Wm - Wd)}{Wd}$$

$$Dm = \frac{Wm}{V}$$

$$Dd = \frac{100\ Dm}{(1+M)}$$

$$C = \frac{100\ Dd}{Dmax}$$

where:

V = volume of the soil sample, m^3
M = moisture content of soil, %
Ws = weight of sand filling hole, kg
Wm = weight of the moist soil, kg
Wd = weight of the dry soil, kg
Ds = density of sand, kg/m^3
Dm = density of the moist soil, kg/m^3
Dd = density of the dry soil (or dry density) kg/m^3
$Dmax$ = maximum theoretical dry soil density, kg/m^3
C = compaction, %

Rate of compaction using rollers can be determined by (Merritt, 1976):

TABLE 3-24
COMPACTION EQUIPMENT

Compactor Type	Soil Best Suited for	Max. Effect in Loose Lift, in.	Density Gained in Lift[a]	Max. Weight, Tons
Steel tandem 2-3 axle	Sandy silts, most granular materials, some clay binder	4-8	Average	16
Grid and tamping rollers	Clays, gravels, silts with clay binder	7-12	Nearly uniform	20
Pneumatic small tire	Sandy silts, sandy clays, gravelly sands and clays, few fines	4-8	Uniform to average	12
Pneumatic large tire	All (if economical)	To 24	Average	50
Sheepsfoot	Clays, clay silts, silty clays, gravels with clay binder	7-12	Nearly uniform	20
Vibratory	Sands, sandy silts, silty sands	3-6	Uniform	30
Combinations	All	3-6	Uniform	20

[a] Density diminishes with depth

Source: Marek, 1977

$$\text{Rate of compaction, m}^3\text{/hr} = \frac{36\ WSLFE}{P}$$

where:

W = width of roller, m

S = roller speed, m/sec

L = lift thickness, cm

F = % reduction in volume due to compaction

E = operator efficiency factor: .90 = excellent; .80 = average; .75 = poor.

P = number of passes made.

Speed of rollers commonly used are:

sheepsfoot rollers,	1.4 m/sec (3.1 mph);
pneumatic rollers,	3.8 m/sec (8.5 mph);
tamping rollers,	4.7 m/sec (10.5 mph); and
grid rollers,	5.7 m/sec (12.8 mph).

Existing cover material should be compacted to a proctor density of 70 to 90 percent of maximum to provide a firm sub-grade (EPA, 1982).

Recommended slopes are:

- 5 percent minimum to enhance runoff and decrease infiltration without risking excessive erosion,
- 6 to 12 percent maximum for top surfaces, and
- 18 percent maximum for side slopes with the center of the site being the highest elevation (EPA, 1982).

Special Precautions and Limitations

None.

3.3.5.4 Principal Data Requirements

Topography (type and extent of grading needed)

Soil characteristics (type grading needed, degree of compaction)

- compaction
- erosion potential (see discussion of erosion control in Section 2).
- moisture content

Storm characteristics (type and extent of grading needed)

Infiltration (type and extent of grading needed)

Runoff (type and extent of grading needed)

Equipment specifications (grading rates)

3.3.5.5 Elements of Cost Review

Components

Construction and Capital--

- equipment
- material added
- hauling

O & M--

- Inspection and maintenance

Major Factors

- size of site

- type and degree of grading required
- additional material needed
- equipment used

Data

Unit costs associated with grading are given in Table 3-25.

Total costs for grading a 20-acre disposal site requiring 5,650 m^3 (7,400 yd^3) of new fill in preparation for cover construction, in 1982 dollars, is $96,000 (EPA, 1982).

3.3.6 Surface Seals

3.3.6.1 Description

Surface seals (caps or covers) are impermeable barriers placed over waste disposal sites to:

- reduce surface water infiltration,
- reduce water erosion,
- reduce wind erosion and fugitive dust emissions,
- contain and control gases and odors, and
- provide a surface for vegetation and other post-closure uses.

Various impermeable materials may be used including soils and clays, admixtures, e.g., asphalt concrete, soil cement, and polymeric membranes, e.g., rubber and plastic linings.

3.3.6.2 Status

Conventional, undemonstrated. Surface sealing is a standard technique in the closure of properly designed disposal sites, and has been used for remedial action. Its effectiveness at uncontrolled sites, however, has not been determined.

TABLE 3-25
UNIT COSTS FOR GRADING

Description	1982 Unit Cost
Topsoil (sandy loam), hauling, spreading and grading (within 20 miles); labor, materials and equipment	\$15.73 /yd^3
On-site excavation, hauling, spreading and compaction of earth (1,000' - 5,000' haul); labor and equipment	\$ 1.19 - 2.62/yd^3
Loam Topsoil; material only	\$ 6.35 /yd^3
Excavate, haul 2 miles, spread and compact loam, sand or loose gravel (with front end loader); labor and equipment only	\$ 2.22 - 2.54 /yd^3
Grading site excavation and fill (no compaction)	
75 h.p. dozer 300' haul	\$ 2.91 /yd^3
300 h.p. dozer, 300' haul	\$ 1.96 /yd^3
Testing soils for compaction	\$35 or 31/sample tested

Source: EPA, 1982

3.3.6.3 Feasibility and Effectiveness

The design of cover systems is discussed in considerable detail in Lutton, et. al., 1979 and in TRD 1. These sources should be consulted if further information is required.

Typical surface seals are composed of several layers, including:

- barrier layer to restrict the passage of water or gas. The barrier has low permeability and usually is composed of clayey soil or a synthetic membrane.
- buffer soil layer above and/or below the barrier layer to protect the barrier layer from cracking, drying, tearing, or from being punctured. It is usually a sandy soil.
- filter layer, made of intermediate grain sizes, to prevent fine particles of the barrier from penetrating and sifting through the coarser buffer layer.
- gas channeling layer of sand and gravel placed immediately above the waste to allow generated gases to escape or be collected. Pipe and trench vents can be used in conjunction with this layer for gas and odor control.
- top soil layer for growth of vegetation.

Two typical layered cover systems are shown in Figure 3-19. and the function of each layer is shown in Table 3-26.

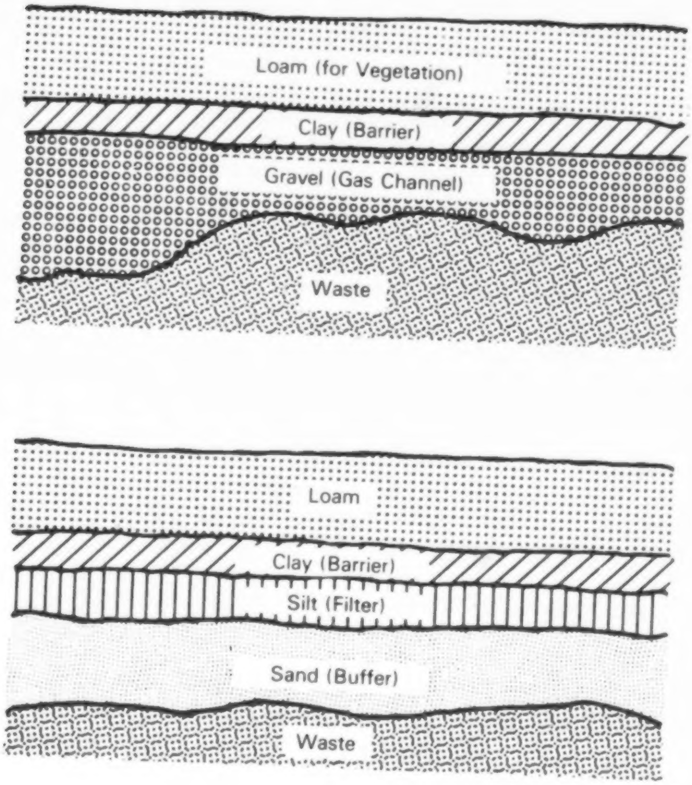
The performance of various soils according to surface seal functions is given in Table 3-27.

The attributes of various chemical additives for cover soils are given in Table 3-28.

Factors supporting the selection of materials for the impermeable layers are given in Table 3-29.

FIGURE 3-19

TYPICAL SURFACE SEALS
(Source: TRD #1)


Loam (for Vegetation)
Clay (Barrier)
Gravel (Gas Channel)
Waste
Loam
Clay (Barrier)
Silt (Filter)
Sand (Buffer)
Waste

Special Precautions and Limitations

None.

3.3.6.4 Principal Data Requirements

Accessibility of cover materials (implementibility and cost)

Soil characteristics (suitability to cover function):

TABLE 3-26
PRIMARY FUNCTION OF COVER LAYERS

Layer	Reduce Infiltration	Reduce Water Erosion	Reduce Wind Erosion/Dust Emissions	Control Gases and Odors	Provide Surface for Vegetation	Enhance Cover Integrity
Barrier	X			X		
Buffer						X
Filter						X
Gas channel				X		
Top soil		X	X		X	X

TABLE 3-27
RANKING OF USCS SOIL TYPES ACCORDING TO PERFORMANCE OF COVER FUNCTION

USCS Symbol	Typical Soils	Trafficability	Water Infiltration		Gas Migration		Erosion Control		Crack Resistance	Support Vegetation
			Impede	Assist	Impede	Assist	Water	Wind		
GW	Well graded gravels, gravel-sand mixtures, little or no fines	E	F	G	F	E	E	E	E	F
GP	Poorly graded gravels, gravel-sand mistures, little or no fines	E	P	E	F	E	E	E	E	F
GM	Silty gravels, gravel-sand-silt mixtures	G	F	F	F	G	G	G	G	F
GC	Clayey gravels, gavel-sand-clay mixtures	G	G	F	G	F	G	G	G	G
SW	Well-graded sands, gravelly sands, little or no fines	E	F	G	F	G	E	E	E	F
SP	Poorly graded sands, gravelly sands, little or no fines	E	P	E	F	G	E	E	E	F
SM	Silty sands, sand-silt mixtures	E-G	F	G	F	G	F	G	E	E
SC	Clayey sands, sand-silt mixtures	G-F	F	F	G	F	F	F	G	E
ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts with slight plasticity	G-F	G	F	G	F	P	F	G	G
CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	F	E	P	E	F	P	F	F	F
OL	Organic silts and organic silty clays of low plasticity	F	-	-	-	-	P	F	F	G
MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	F	G	F	-	-	F	F	F	G
CH	Inorganic clays of high plasticity, fat clays	F	E	P	E	F	F	F	F	F
OH	Organic clays of medium to high plasticity, organic silts	P	-	-	-	-	F	-	F	F
Pt	Peat and other highly organic soils	P	-	-	-	-	G	-	-	G

Key: E = Excellent; G = Good; F = Fair; P = Poor

Source: Lutton, et.al., 1979

TABLE 3-28
CHEMICAL ADDITIVES FOR COVER SOIL

	Attribute*			
Category and Agent	Strength	Water	Dust/Wind	Comments**
Inorganic chemicals				
Calcium chloride	Yes	Yes	Yes	Maintains moisture content. Easily leached out by water.
Lime	Yes			See discussion in text.
Phosphoric acid	Yes			Cementing agent. Mixes easily with soil.
Potassium silicate			Yes	---
Sodium carbonate				See discussion in text.
Sodium chloride	Yes			Easily leached out by water.
Sodium silicate			Yes	Effective in well-graded, compacted sand.
Sodium silicate N		Yes	Yes	Forms hard crust after 1-hour cure. Effective in sands.
Sodium silicate No. 9		Yes		Effective when sprayed on. Approximate cost $0.60/gal.
Soil lok			Yes	Combination sodium silicate and calcium chloride. Effective in fine-grained soils. Forms hard surface.
Resinous materials				
Aerospray 52		Yes		Alkyd resin emulsion that forms a hard crust. Approximate cost $2.85/gal.
Aerospray 70		Yes		Polyvinyl acetate resin emulsion. Effective in sand. Approximate cost $2.50/gal.
AM-9	Yes		Yes	Blend of water-soluble acrylamide and diacrylamide. Provides flexible surface after long curing.
Amoco A	Yes			Requires moisture and temperatures above 40°F (4°C) to cure. Effective mixed with sand.
Amoco B	Yes			Fast curing resin. Effective mixed with sand.
Aniline-furfural	Yes	Yes	Yes	Provides tough surface for dry silt and clay. Soil moisture reduces final strength Toxic.
Aniline hydrochloride furfural	Yes			Nontoxic resin. Effective in highly acid or neutral soils with PI's of 3 to 20.
Aroplaz 6065		Yes		---
Aropol 7110	Yes		Yes	Unsaturated polyester resin. Significantly increases soil strength of sand, silt, or clay.
Aropol 7720 M			Yes	Unsaturated polyester resin. Effective in sand, silt, or clay.
Arothane 156		Yes		Polyurethane elastomer with rapid curing.

(Continued)

TABLE 3-28
CHEMICAL ADDITIVES FOR COVER SOIL (Cont.)

Category and Agent	Attribute*			Comments**
	Strength	Water	Dust/Wind	
Resinous materials (continued)				
Arothane 160	Yes	Yes	Yes	Polyurethane elastomer with rapid curing. Effective in clay.
Arothane 170	Yes	Yes	Yes	Similar to Arothane 160.
Ashland CR 726	Yes			Blend of resorcinol and an accelerator. Effective mixed with clay.
Base 792-D			Yes	Blend of polyvinyl resins and modifiers.
Base 792-L			Yes	Similar to Base 792-D.
Celanese 13-67-5	Yes			---
Celanese 510+872	Yes			Blend of EpiRez 510 and EpiCure 872. Effective mixed with sand.
Celanese 16-78-16	Yes			Blend of EpiRez 510, 544, and EpiCure 8701. Requires moisture to cure. Effective mixed with sand.
Celanese 16-78-1	Yes			Blend of EpiRez 510, 856, and EpiCure 87. Effective mixed with sand or clay.
Celanese 16-77-1	Yes			---
Chem-Rez 200			Yes	Furfural based rapid setting resin. Effective in sand or clay.
Chrome lignin		Yes		Risinous alkali waste and a hexavalent chromium compound in gel form.
CIBA 509+X8157/136	Yes			Blend of Araldite 509 and X8157/136. Effective mixed with clay.
CIBA 6010+X8157/136	Yes			Blend of Araldite 6010 and X8157/136. Effective with sand or clay of variable moisture content.
CIBA 6010+X8157/157	Yes			---
DCA-70	Yes		Yes	Emulsion of polyvinyl acetate and chemical modifiers. Cures in 2 to 4 hours. Can be reinforced with fiberglass filaments.
DCA-1295	Yes		Yes	Improved DCA-70. Fiberglass reinforcement may be harmful if inhaled or blown into eyes.
Dow CX-7	Yes			Blend of vinyl ester resin, benzoyl peroxide, and N. N. dimethylanitine. Fast curing. Effective mixed with sand.
Dow derakene 114	Yes			Blend of vinyl ester resin, benzoyl peroxide, and N. N. dimethylanitine. Requires moisture to cure. Effective mixed with sand or clay.
Dresinate DS-60W-80F		Yes		Thermoplastic resin. Effective in spray applications. Approximate cost $0.34/gal.
Edoco X-2111-1	Yes			Effective in sand or clay.
Emlon E-200	Yes	Yes	Yes	Water soluble resin that cures within 2 hours in combination with diethylene triamine. Effective in sand or clay.

(Continued)

Table 3-28
CHEMICAL ADDITIVES FOR COVER SOIL (Cont.)

Category and Agent	Attribute* Strength	Water	Dust/Wind	Comments**
Resinous materials (continued)				
Epon 828		Yes	Yes	Epoxy resin with slow curing time. Penetrates sand or clay and forms a hard crust.
Epon 828+V40	Yes			Blend of Epon 828 and V40. Effective in sand or clay.
General latex-vultex	Yes			Blend of an epoxy resin and a catalyst. Causes low strength gain.
General Mills TSX-429+TSX-428	Yes			Blend of a resin and a coreactive resin. Causes low strength gain.
HK-1			Yes	1:1 mix of Base 792-D and 792-L.
HK-2	Yes		Yes	3:1 mix of Base 792-D and 792-L. Forms tough resilient film but curing can take more than 7 hours with loose sand in humid conditions.
Jones-Dabney No. 6	Yes			Blend of EpiRez 5159, 5044, and EpiCure 874. Effective in sand or clay.
Jones-Dabney No. 7	Yes			---
Lignin liquor			Yes	Resinous alkali waste and compounds.
Ligno sulfonates	Yes	Yes	Yes	See Norlig 41.
Lino-cure C		Yes		Foundry resin that forms a hard, waterproof surface when applied with ethylene glycol.
Norlig 41	Yes	Yes	Yes	Ligno sulfonate. Approximate cost $0.27/gal.
Orzan	Yes	Yes	Yes	Mixture of ligno sulfonate and chemicals. Forms shrinkage cracks when cured. May be leached out by water.
Paracol TC1842			Yes	Resin emulsion. Good results with mine tailings.
Paracol S1461			Yes	Blend of wax and resin. Effective with mine tailings. Approximate cost $0.39/gal.
Petroset RB	Yes	Yes	Yes	Emulsion of resins, elastomer, and volatile solvents. Effective in gravel and rock. Approximate cost $2/gal.
Petroset SB	Yes	Yes	Yes	Emulsion of resins, elastomer, oils, solvents, and water. Effective in particles below gravel size. Approximate cost $1.60/gal.
R 20		Yes		Sodium methyl silanolate. Nonbiogradable. Approximate cost $0.05/yd^2 treated.
Resinox 9673		Yes		---
Resin 321		Yes		Finely powdered resinous substance. Effective in acid soils (silty clay and clayey silt).

(Continued)

TABLE 3-28
CHEMICAL ADDITIVES FOR COVER SOIL (Cont.)

Category and Agent	Attribute*			Comments**
	Strength	Water	Dust/Wind	
Resinous materials (continued)				
Soil seal			Yes	Emulsion of material copolymers in the plastic resin range. Effective in fine-grained sand.
Vinsol		Yes		Powdered resinous substance. Effective in sandy silt, silty sand, clayey silt, and clayey sand. Susceptible to microbial attack.
Vistron silmar S-3840	Yes			Modified polyester resin. Requires moisture to cure. Causes low strength gains.
Whitesides 69-Y-1	Yes			Emulsified epoxy resin. Effective mixed with clay.
Polymeric materials				
Compound SP 301		Yes		Latex copolymer emulsion. Effective in spray application. Approximate cost $1.30/gal.
Curasol AE			Yes	Polyvinyl acetate latex dispersion. Forms a hard crust. Cleanup is difficult. Approximate cost $2.60/gal.
Curasol AH			Yes	Polyvinyl acetate latex. Forms a flexible crust.
Neoprene 750	Yes		Yes	---
Petroset RB	Yes	Yes	Yes	See Resinous materials.
Petroset SB	Yes	Yes	Yes	See Resinous materials.
Petroset AX	Yes	Yes	Yes	Emulsion of elastomer, asphalt, solvents, and water.
Petroset AT	Yes	Yes	Yes	Emulsion of elastomer, oils, and water.
Polyco 2460		Yes		Styrene/butadiene latex. Effective in spray applications. Approximate cost $0.87/gal.
Surfaseal			Yes	Viscous plastic material. May require several applications, allowing drying time prior to each additional application. Approximate cost $4.40/gal.
Terra-krete			Yes	Chemicals in latex base. Forms hard surface.
Ucar 130			Yes	Polyvinyl acetate.
Vultex 1-V-10			Yes	Prevulcanized rubber latex.
White soil stabilizer		Yes		Latex polymer, effective mixed with soil. Approximate cost $4.31/gal.
Bituminous materials				
APSB (Asphalt penetrative soil binder)			Yes	Low penetration grade asphalt, kerosene, and naptha. Good penetration in impervious or tight soils. Cures in 6 to 12 hours. Flammable.

(Continued)

TABLE 3-28 (Continued)

	Attribute*			
Category and Agent	Strength	Water	Dust/Wind	Comments**
Bituminous materials (continued)				
Liquid shale tar (shale oil)	Yes			Effective in sand or clay.
Peneprime			Yes	Same as APSB.
Petroset AX	Yes	Yes	Yes	See Polymeric materials.
Miscellaneous materials				
Admex 710			Yes	---
Aggrecote 600			Yes	---
Aquatin		Yes		Concentrate of chemicals and pectin. Forms fragile crust. Stains skin, clothing, and equipment. Approximate cost $2.30/gal.
Bio-binder		Yes		For spray applications. Approximate cost $2.57/gal.
Bisphenol A			Yes	---
Calcium acrylate	Yes	Yes		Organic salt that forms strong bonds in wet, fine-grained soils.
Calcium sulfonate		Yes		---
Cyanaloc 62		Yes	Yes	---
Dust bond 100		Yes		Approximate cost $0.36/gal.
Dustrol		Yes	Yes	Medium grade road oil. Flammable.
ELO			Yes	---
Formula 125		Yes		Organic cementing agent and a sodium methyl siliconate base. Effective in gravel to clay. Caustic in concentrated form. Approximate cost $10/gal.
Gelatin 15XPF		Yes		Good penetration in sand. Forms hard, brittle surface.
Goodyear X335			Yes	---
Heavetex P1396	Yes			---
Heavetex P1397	Yes			---
Hysol	Yes			---
K-aton 101			Yes	---
Landlock			Yes	---
Lemac 40			Yes	---
Orzan GL-50		Yes		Cementing material that can be sprayed or mixed with soil. Approximate cost $0.30/gal.
Pacific N 748 N	Yes		Yes	---

(Continued)

TABLE 3-28
CHEMICAL ADDITIVES FOR COVER SOIL (Cont.)

Category and Agent	Attribute*			Comments**
	Strength	Water	Dust/Wind	
Miscellaneous materials (continued)				
Stabinol		Yes		3:1 mix of Portland cement and Resin 321 or a complex salt. Deteriorates after long storage.
Sulfite liquor	Yes			Effective sprayed on sand and gravel. Easily leached out by water.
Terra-krete No. 2		Yes		Inorganic and organic materials with a synthetic binder. Approximate cost $2.50/gal.
Tung oil		Yes		---
Waste oil	Yes	Yes	Yes	---

* Attributes are marked yes where addition to soil is claimed (not necessarily substantiated) to stabilize generally, to repell water or resist water erosion, or to resist dusting or wind erosion. Dispersants are another group of additives used primarily to aid in the compacting process; they are not included in this table but are discussed in the text.

** The pollution potential of additives should be given special consideration prior to usage.

Source: Lutton et al., 1979

- type (USCS or USDA classification)
- grain size distribution
- compaction
- strength properties
- erosion potential
- permeability
- capillary head
- clay mineralogy

Waste characteristics (cover function requirements):

- chemical
- physical
- disposal practices

TABLE 3-29
PRODUCTS RECOMMENDED FOR PRIORITY COVER

Material and Description	Advantages	Disadvantages
Bitumen cements or concretes (AC-40 and AC-20 viscosity grades.)	a. Provide tight, impervious barriers covering municipal/hazardous waste. b. Good availability. c. May be used as thick waterproofing layers in flat areas or on slopes.	a. Expensive b. Special heating and storage equipment required for handling. c. Vulnerable to breaking.
Portland cements or concretes (3000 psi and 5000 psi)	a. Good availability. b. Provides good highly impermeable containers or covers for hazardous waste disposal. Very low water permeability.	a. May crack during curing, allowing potential paths for escaping gases or infiltrating water. b. Leakage from hazardous wastes in liquid form may weaken concrete with time
Liquid and emulsified asphalts (RC and EC 30, 70, 250, 800, and 3000 liquid asphalts. RS's and CRS's 1 and 2, MS's emulsion.)	a. Can be sprayed on soil covers to decrease water and gas permeability b. Can be mixed with soil to form waterproof layer. c. Penetrate open surfaces, plug voids, then cure. d. Penetrate tight surfaces, plug voids, then cure. e. Provide hard, tight, stable membrane (RC and MC 800 and 3000)	a. Must leave sprayed surface exposed until it either cures (RC's, MC's) or sets (SS's). b. Must be covered for protection. c. Require additional equipment to handle and apply the asphalts. Spraying temperatures range from 75° to 270°F (25° to 130°C). d. Use of RC and MC 800 and 3000 in thick membrane construction may require numerous applications.
Tars (RT 1, 2, 3, 4, 7, 8, and 9. RTCB 5 and 6).	a. Can be sprayed on soil surfaces or mixed with particles. Tars mix well with wet aggregate. b. Penetrate tightly bonded soil surfaces and plug voids (RT 1 and 2). c. Penetrate loosely bonded fine aggregate surfaces and plug voids (RT 2, 3, and 4). d. Penetrate loosely bonded coarse aggregate surfaces and plug voids (RT 3 and 4). e. Low spray on temperatures 60° to 150°F (15° to 65°C) for RT 1, 2, 3, and 4 and RTCB 5 and 6. f. Provide hard, tight, stable surface membrane (RT 7, 8, and 9). May be used in flat areas or on slopes. g. Provide good penetration, then cure to form hard surface (RTCB 5 and 6).	a. Tar may be removed by traffic if not covered with a protective soil layer. b. Tars are more susceptible to weathering effects than asphalts. Must be protected from weathering. c. Require special equipment for handling and application. d. RT 7, 8, and 9 require application temperatures of 150° to 225°F (65° to 105°C).
Bituminous fabrics	a. Require minimal special equipment and skill. b. Resist tearing.	a. Expensive b. Laps should be sealed.
Commercial polumeric membranes (Butyl rubber)	a. Available in various size sheets. b. Can be reinforced with fibers for added strength. c. Can be joined at seams to cover d. Good availability. e. Good heat resistance.	a. Poor resistance to weathering and abrasion. b. May be damaged by gnawing/burrowing animals if not protected with soil. c. May be damaged by heavy equipment operating directly on surface and may be punctured by large stones or sharp edges in direct contact.

TABLE 3-29
PRODUCTS RECOMMENDED FOR PRIORITY COVER (Cont.)

Material and Description	Advantages	Disadvantages
	f. Very low water permeability. g. Low vapor transmissivity.	
Commercial polymeric membranes (continued)		
(Neoprene rubber (chloroprene rubber))	a. Good resistance to oils, grease, gasoline, acids, and alkalies. b. Good resistance to abrasion, weathering, and flexing. c. Can be joined at seams to cover large areas. d. Can be reinforced with fibers for added strength. e. Very low water permeability.	a. More expensive than other natural and synthetic rubbers. b. Use is limited to special applications because of a above. c. May be damaged by gnawing/burrowing animals if not protected with a soil layer. d. May be damaged by heavy equipment operating directly on surface and may be punctured by large stones or sharp edges in direct contact.
(Hypalon (chlorinated chlorosulfinated polyethylene))	a. Outstanding resistance to abrasion and weathering. b. Available in various size sheets. c. Can be fiber reinforced for added strength. d. Can be joined at seams to cover large areas. This can be done onsite or at factory. e. Very low water permeability.	a. May be damaged by gnawing, burrowing animals if not protected with a soil layer. b. Does not perform satisfactorily when exposed to amyl acetate, benzene, carbon tetrachloride, creosote oil, cyclohexane, dioctyl phthalate, ethyl acetate, lacquer methylene chloride, napthalene, nitrobenzene, oleum, toluene, tributyl phosphate, trichloroethylene, turpentine, and xylene. c. For good seam quality, the weather must be at least 50°F (10°C) and sunny. If not, heat has to be applied to seams to develop full early strength. d. May be damaged by heavy equipment operating directly on membrane. e. May be punctured by large stones on sharp edges in direct contact.
(Polyolefin (polyethylene and chlorinated polyethylene))	a. Available in various sizes. b. Can be joined at seams to cover large areas. c. Can be fiber reinforced. d. Chlorinated polyethylene has excellent outdoor durability. e. Very low water permeability.	a. May be damaged by gnawing/burrowing animals if not protected with a soil layer. b. May be damaged by heavy equipment operating directly on membrane. c. May be punctured by large stones or sharp edges in direct contact. d. Polyethylene has poor durability when exposed.
(Elasticized polyolefin (3110))	a. Can be joined at seams to cover large areas. Field bonding of individual sheets is done using a heat seaming techniques. b. Excellent resistance to soil micro-organisms, extremes of weather, and ozone attack. c. Very low water permeability.	a. May be damaged by gnawing/burrowing animals if not protected with a soil layer. b. May be damaged by heavy equipment operating directly on membrane. c. May be punctured by large stones or sharp edges in direct contact with membrane.

TABLE 3-29
PRODUCTS RECOMMENDED FOR PRIORITY COVER (Cont.)

Material and Description	Advantages	Disadvantages
Commercial polymeric membranes (continued)		
(PVC (polyvinyl chloride)	a. Fair outdoor durability. b. Available in sheets of various sizes. Factory seaming available c. Seams can be bonded in the field with vinyl to vinyl adhesive. d. Generally used without reinforcement, however, can be fiber reinforced for special applications. e. Very low water permeability. f. Less permeable to gas than polyethylene.	a. May be damaged by gnawing/burrowing animals if not protected with a soil layer. b. For extended life, this membrane must be covered with soil or other material. c. May be damaged by heavy equipment d. Not as durable as hypalon or chlorinated polyethylene. e. Becomes stiff in cold weather.
(EPDM (ethylene-propylene-unsaturated diene terpolymer))	a. Good outdoor durability. Ozone and oxidation resistant. b. Sheets may be bonded to cover large areas. c. Very low water permeability.	a. May be damaged by gnawing/burrowing animals if not protected with a soil layer. b. May be damaged by heavy equipment operating directly on surface and may be punctured by large stones or sharp edges in direct contact.
Sulfur (thermoplastic coating) (Molten sulfur)	a. Can be formulated for a wide range of viscosities. b. Can be sprayed on various materials to act as a bonding agent. c. Reduces permeability. d. Resistant to weather extremes (subfreezing to very hot). e. Resistant to acids and salts. f. Can be mixed with fine aggregate to form a type of concrete.	a. Requires high temperatures for workability, 250° - 300°F (20° - 150°C). b. Requires special equipment for handling and application. c. May not tolerate much shear deformation. d. If applied to hazardous waste containers prior to land disposal, heat absorption by volatile wastes may cause gas expansion and possible explosion hazards.
Bentonite	a. No special equipment needed. b. Can be mixed with soil.	a. Difficult to handle and spread after wetting. b. Susceptible to shrink-swell.

Source: Lutton et al, 1979

Climatology (cover function requirements):

- precipitation
- evapotranspiration
- storm characteristics
- wind characteristics
- air quality

Infiltration (cover function requirements)

Runoff (cover function requirements)

3.3.6.5 Elements of Cost Review

Components

Construction and Capital--

- material for various layers
- equipment
- transportation

O & M--

- Inspection and maintenance

Major Factors

- size of site
- layers required
- material used for each layer
- transportation

Data

Unit cost for surface seals are given in Table 3-30.

Unit costs for a bituminous concrete seal 55,000 m^2, including excavation and grading, in 1982 dollars, is \$275,000 - \$379,000 (SCS, 1980).

3.3.7 Vegetation

3.3.7.1 Description

Vegetation can perform four basic functions:

- It can stabilize soil and earthen structures against wind and water erosion by intercepting rainfall, slowing runoff, and holding soil together with a tight root system.
- It can reduce the quantities of water available for runoff through interception, infiltration, uptake and transpiration.
- It can treat contaminated soil and leachate through the uptake and removal of waste constituents, nutrients, and water from the soil.
- It can improve the aesthetic appearance of the site.

Plants used for revegetation include various types of grasses, legumes, shrubs and trees. A revegetation program involves careful plant selection, land preparation (such as increasing soil depth, grading, fertilizing and tilling), seeding, and maintenance.

3.3.7.2 Status

Conventional, demonstrated.

3.3.7.3 Feasibility and Effectiveness

TABLE 3-30
UNIT COSTS FOR SURFACE SEALS

Cover Material and/or Method of Installation	1982 Unit Costs
Topsoil (sandy loam), hauling, spreading and grading (within 20 miles)	$\$15.73/\mathrm{yd}^3$
Clay hauling, spreading and compaction	$\$16/29/\mathrm{yd}^3$
Sand hauling spreading and compaction	$\$18.15/\mathrm{yd}^3$ $9,680-12,200-acre
Cement concrete (4 to 6" layer), mixed, spread compacted on-site	$\$7.26\text{-}12.10/\mathrm{yd}^2$
Bitumeonus concrete (4 to 6" layer, including base layer)	$\$3.81\text{-}6.35/\mathrm{yd}^2$
Lime or cement, mixed into 5" cover soil	$\$1.91\text{-}2.67/\mathrm{yd}^2$
Bentonite, material only; 2" layer, spread and compacted	$\$1.78/\mathrm{yd}^2$
Sprayed asphalt membrane (1/4 layer and soil cover), installed	$\$1.91\text{-}3.18/\mathrm{yd}^2$
PVC membrane (20 mil), installed	$\$1.65\text{-}2.54/\mathrm{yd}^2$
Chlorinated PE membrane (20-30 mil), installed	$\$3.05\text{-}4.06/\mathrm{yd}^2$
Elasticized polyolefin membrane, installed	$\$3.27\text{-}4.36/\mathrm{yd}^2$
Hypalon^R membrane (30 mil), installed	$\$7.87/\mathrm{yd}^2$
Neoprene membrane, installed	$\$6.05/\mathrm{yd}^2$
Ethylene propylene rubber membrane, installed	$\$3.43\text{-}4.44/\mathrm{yd}^2$
Butyl rubber membrane, installed	$\$3.43\text{-}4.83/\mathrm{yd}^2$
Teflon-coated fiberglass (TFE) membrane (10 mil), installed	$\$24.20/\mathrm{yd}^2$
Fly ash and/or sludge, spreading, grading and rolling	$\$1.27\text{-}2.16/\mathrm{yd}^3$

Source: EPA, 1982

Characteristics

Important characteristics of selected grasses, legumes, shrubs, and trees are given in Tables 3-31 through 3-34. A concise list of the major characteristics of over 800 species of plants can be found in Dukes, 1978.

Selection

Selection of vegetation will depend on site-specific requirements and plant characteristics. In general, grasses provide quick and lasting dense growth. They effectively anchor the soil, have high evapotranspiration characteristics, and may be suitable in wet areas such as waterways. They do, however, require periodic mowing and maintenance (TRD 11).

Legumes, on the other hand, are a low maintenance cover providing long-term protection. They are most suitable for stabilization and erosion control and are useful even on steep slopes. They also have the added benefit of increasing soil fertility through nitrogen fixation (TRD 11).

Shrubs are useful in providing a dense surface cover and are tolerant to acidic soils (TRD 11).

Trees are most suited to preparing a site for post-closure use. They help provide a long-term protective cover and build up a stable, fertile layer of decaying leaves and branches (EPA, 1982).

Indigeneous species (those growing naturally in the site region) should be used wherever possible (TRD 11).

Maintenance

Temporary stabilization against erosion may be required while vegettation is being established. Techniques include:

- straw-bale check dams (for waterways)

TABLE 3-31
CHARACTERISTICS OF COMMONLY USED GRASSES

Common name	Season			Site suitability				Growth habit[b]	pH range[c]	Use suitability			Remarks
	Cool	Warm	Dry (not droughty)	Well drained	Moderately well drained	Somewhat poorly drained	Poorly drained			Erodible areas	Waterways and channels	Agriculture[d]	
Bahiagrass		X	X	X	X			P	4.5-7.5	X	X	X	Tall, extensive root system. Maintained at low cost once established. Able to withstand a large range of soil conditions. Scarify seed.
Barley	X			X	X			A	5.5-7.8	X		X	Cool season annual. Provides winter cover.
Bermuda grass		X	X	X	X	X		P	4.5-7.5	X	X	X	Does best at a pH of 5.5 and above. Grows best on well drained soils, but not on waterlogged or tight soils. Propagated vegetatively by planting runners or crowns.
Bluegrass, Canada	X		X	X	X			P	4.5-7.5	X		X	Does well on acid, droughty, or soils too low in nutrients to support good stands of Kentucky bluegrass.
Bluegrass, Kentucky	X			X	X	X		P	5.5-7.0	X	X	X	Shallow rooted; best adapted to well-drained soils of limestone origin.
Bluestem, big		X		X	X	X		P	5.0-7.5	X		X	Strong, deep rooted, and short underground stems. Effective in controlling erosion.
Bluestem, little		X		X	X			P	6.0-8.0	X		X	Dense root system; grows in a clump to 3 feet tall. More drought tolerant than big bluestem. Good surface protection.
Bromegrass, field	X			X	X	X		A	6.0-7.0	X		X	Good winter cover plant. Extensive fibrous root system. Rapid growth and easy to establish.
Bromegrass, smooth	X		X	X	X	X		P	5.5-8.0	X	X	X	Tall, sod forming, drought and heat tolerant. Cover seed lightly.
Buffalograss		X			X	X		P	6.5-8.0	X		X	Drought tolerant. Withstands alkaline soils but not sandy ones. Will regenerate if overgrazed.
Canarygrass, reed	X		X	X	X	X	X	P	5.0-7.5	X	X	X	Excellent for wet areas, ditches, waterways, gullies. Can emerge through 6 to 8 inches of sediment.
Deertongue		X	X	X	X	X	X	P	3.8-5.0	X	X		Very acid tolerant; drought resistant. Adapted to low fertility soils. Volunteers in many areas. Seed not available.
Fescue, creeping red	X		X	X	X	X		P	5.0-7.5	X	X	X	Grows in cold weather. Remains green during summer. Good seeder. Wide adaptation. Slow to establish.
Fescue, tall	X			X	X	X		P	5.0-8.0	X	X	X	Does well on acid and wet soils of sandstone and shale origin. Drought resistant. Ideal for lining channels. Good fall and winter pasture plant.
Grama, blue		X	X	X	X	X		P	6.0-8.5	X			More drought resistant than sideoats grama. Sod forming. Extensive root system. Poor seed availability.
Grama, sideoats		X		X	X			P	6.0-7.5	X		X	Bunch forming; rarely forms a sod. May be replaced by blue grama in dry areas. Feed value about the same as big bluestem. Helps control wind erosion.
Indian grass		X			X	X		P	5.5-7.5	X		X	Provides quick ground cover. Rhizomatous, tall. Seed available.
Lovegrass, sand		X		X				P	6.0-7.5	X		X	A bunchgrass of medium height. Adaptable to sandy sites. Good for grazing. Fair seed availability.
Lovegrass weeping		X	X	X	X	X		P	4.5-8.0	X			Bunchgrass, rapid early growth. Grows well on infertile soils. Good root system. Low palatability. Short-lived in Northeast.

TABLE 3-31
CHARACTERISTICS OF COMMONLY USED GRASSES (Cont.)

Common name	Season			Site suitability				Growth habit[b]	pH range[c]	Use suitability			Remarks
	Cool	Warm	Dry (not droughty)	Well drained	Moderately well drained	Somewhat poorly drained	Poorly drained			Erodible areas	Waterways and channels	Agriculture[d]	
Millet, foxtail		X	X	X	X			A	4.5-7.0	X		X	Requires warm weather during the growing season. Cannot tolerate drought. Good seedbed preparation important.
Oats	X		X	X				A	5.5-7.0	X		X	Bunch forming. Winter cover. Requires nitrogen for good growth.
Oatgrass, tall	X		X	X				P	5.0-7.5	X		X	Short-lived perennial bunchgrass, matures early in the spring. Less heat tolerant than orchardgrass except in Northeast. Good on sandy and shallow shale sites.
Orchardgrass	X		X	X	X	X		P	5.0-7.5	X		X	Tall-growing bunchgrass. Matures early. Good fertilizer response. More summer growth than timothy or bromegrass.
Redtop	X		X	X	X	X	X	P	4.0-7.5	X	X	X	Tolerant of a wide range of soil fertility, pH, and moisture conditions. Can withstand drought; good for wet conditions. Spreads by rhizomes.
Rye, winter	X		X	X	X			A	5.5-7.5	X		X	Winter hardy. Good root system. Survives on coarse, sandy spoil. Temporary cover.
Ryegrass, annual	X			X	X	X		A	5.5-7.5	X		X	Excellent for temporary cover. Can be established under dry and unfavorable conditions. Quick germination; rapid seedling growth.
Ryegrass, perennial	X			X	X	X		P	5.5-7.5	X		X	Short-lived perennial bunchgrass. More resistant than weeping love or tall oatgrass.
Sandreed, prairie		X	X	X				P	6.0-8.0	X			Tall, drought tolerant. Can be used on sandy sites. Rhizomatous. Seed availability poor.
Sudangrass		X	X	X	X	X		A	5.5-7.5	X		X	Summer annual for temporary cover. Drought tolerant. Good feed value. Cannot withstand cool, wet soils.
Switchgrass		X		X	X	X		P	5.0-7.5	X	X	X	Withstands eroded, acid and low fertility soils. Kanlow and Blackwell varieties most often used. Rhizomatous. Seed available. Drainageways, terrace outlets.
Timothy	X			X	X	X	X	P	4.5-8.0	X		X	Stands are maintained perennially by vegetative reproduction. Shallow, fibrous root system. Usually sown in a mixture with alfalfa and clover.
Wheat, winter	X		X	X	X	X		A	5.0-7.0	X		X	Requires nutrients. Poor growth in sandy and poorly drained soils. Use for temporary cover.
Wheatgrass, tall	X		X	X	X	X	X	P	6.0-8.0	X	X	X	Good for wet, alkaline areas. Tolerant of saline conditions. Sod forming. Easy to establish.
Wheatgrass, western	X		X	X	X	X	X	P	4.5-7.0	X	X	X	Sod forming, spreads rapidly, slow germination. Valuable for erosion control. Drought resistant.

[a] Grasses should be planted in combination with legumes. Seeding rates, time, and varieties should be based on local recommendations.

[b] P = perennial; A = annual.

[c] Many species survive and grow at lower pH; however, optimum growth occurs within these ranges.

[d] Hay, pasture, green manure, winter cover, and nurse crops are primary agricultural uses.

Source: EPA, 1976, Vol. 1

TABLE 3-32
CHARACTERISTICS OF COMMONLY USED LEGUMES

Common name	Season			Site suitability				Growth habit[b]	pH range[c]	Use suitability			Remarks
	Cool	Warm	Dry	Well drained	Moderately well drained	Somewhat poorly drained	Poorly drained			Erodible areas	Waterways and channels	Agriculture[d]	
Alfalfa	X		X	X	X			P	6.5-7.5	X		X	Requires high fertility and good drainage.
Clover, Alsike	X			X	X	X	X	P	5.0-7.5	X		X	Good for seeps and other wet areas. Dies after 2 years.
Clover, red	X			X	X			P	6.0-7.0	X		X	Should be seeded in early spring.
Clover, white	X			X	X	X		P	6.0-7.0	X		X	Stand thickness decreases after several years.
Flatpea	X		X	X	X	X		P	5.0-6.0	X			Seed is toxic to grazing animals. Good cover.
Lespedeza, common		X		X	X			A	5.0-6.0	X			Low-growing, wildlifelike seed. Kobe variety most often used. Acid tolerant.
Lespedeza, Korean		X	X	X	X	X		A	5.0-7.0	X			Less tolerant of acid soils than common lespedeza.
Lespedeza, sericea		X	X	X	X	X		P	5.0-7.0	X	X		Woody, drought tolerant, seed should be scarified. Bunchlike growth.
Milkvetch, cicer			X	X	X	X		P	5.0-6.0	X		X	Drought tolerant. Low growing. No major diseases. Hard seed coat.
Sweetclover, white	X		X	X	X			B	6.0-8.0	X		X	Requires high-pH spoil. Tall growing. Produces higher yields. Less reliable seed production.
Sweetclover, yellow	X		X	X	X			B	6.0-8.0	X		X	Requires high-pH spoil. Tall growing. Can be established better than white sweetclover in dry conditions.
Trefoil, birdsfoot	X		X	X	X	X		P	5.0-7.5	X		X	Survives at low pH. Inoculate with special bacteria. Plant with a grass.
Vetch, crown	X		X	X	X			P	5.5-7.5	X		X	Excellent for erosion control. Drought tolerant. Winter hardy.
Vetch, hairy	X		X	X	X			A	5.0-7.5	X		X	Adapted to light sandy soils as well as heavier ones. Used most often as a winter cover crop.

[a] Legumes should be inoculated. Use four times normal rate when hydroseeding.

[b] A = annual; B = biennial; P = perennial.

[c] Many species survive and grow at lower pH; however, optimum growth occurs within these ranges.

[d] Hay, pasture, green manure.

Source: EPA, 1976, Vol. 1

TABLE 3-33
CHARACTERISTICS OF COMMONLY USED TREES

Common Name	Remarks
Trees, conifers:	
Virginia pine	Tolerant of acid spoil. Use for esthetics and where other species will not survive. Slow development. Good for wildlife.
Pitch pine	Deep rooted and very acid tolerant. Can survive fire injury. Deer like small seedlings. Plant in bands or blocks.
Loblolly pine	Very promising species, rapid early growth. Marketable timber products. Can survive pH 4.0 to 7.5. Susceptible to ice and snow damage.
Scotch pine	Good for Christmas trees if managed properly. Can be planted on all slopes and tolerates pH of 4.0 to 7.5.
Shortleaf pine	Some insect problems. Will sprout freely if cut or fire killed when young. Good marketable timber.
White pine	May be used for Christmas trees. Has poor initial growth but improves with time. Plant in bands or blocks.
Austrian pine	Can be planted on all slopes. Plant in bands or blocks. When planted near black locust, deer cause browse damage.
Japanese larch	Should be planted on unleveled and noncompacted spoil. Provides good litter.
Red pine	Sawfly damage in some areas. Plant on all slopes. Light ground cover.
Rocky Mountain juniper	Has shown good survival on Kansas spoil materials. Compact growth varieties have from silver to purple colors.
Eastern red cedar	Tall, narrow growth. Best on dry, sandy soils. Good with black locust. pH 5.0 to 8.0.
Mugho pine	Survives on acid spoil. Develops slowly. Low growing. Good cover for wildlife.
Trees, hardwoods:	
Black locust	Can be direct seeded. Wide range of adaptation. Rapid growth; good leaf litter. Use mixed plantings. Dominant stem clones preferred.
Bur oak	Better survival with seedling transplants than acorns. Light to heavy ground cover.
Cottonwood	A desirable species for large-scale planting. Good cover and rapid growth. Pure stands should be planted.
European black alder	Rapid growing. Wide adaptation. Nitrogen fixing, nonlegume. Can survive pH 3.5 to 7.5. Adapted to all slopes.
Green ash	Very promising species. Use on all slopes and graded banks with compact loams and clays. Plant in hardwood mixture.
Hybrid poplar	Rapid growth. Good survival at low pH. Marketable timber after 20 years. Cannot withstand grass competition. Good for screening.
Red oak	Makes slow initial growth. Good survival, plant on upper and lower slopes only. Can grow from pH 4.0 to 7.5.
European white birch	Makes rapid growth on mine spoil. Poor leaf litter and surface coverage.
Sycamore	One of the most desirable species for planting. Poor ground cover. Volunteer trees grow faster than planted ones.

Source: EPA, 1976, Vol. 1

TABLE 3-34
CHARACTERISTICS OF COMMONLY USED SHRUBS

Common Name	Remarks
Shrubs:	
Amur honeysuckle	Good for wildlife. Shows more vigor and adaptability as plants mature.
Bristly locust	Extreme vigor. Thicket former. Good erosion control. Rizomatous, 5-7 ft tall. Excellent on flat areas and outslopes.
Autumn-olive	Nitrogen-fixing nonlegume. Good for wildlife. Excellent fruit crops. Wide adaptation. Up to 15 ft tall.
Bicolor lespedeza	Can be established from planting and direct seeding. Ineffective as a ground cover for erosion control.
Indigo bush	Has high survival on acid spoil. Leguminous. Not palatable to livestock. Thicket former. Slow spreader. 8-12 ft tall.
Japanese fleeceflower	Grows well on many sites, especially moist areas. Excellent leaf litter and canopy protection. pH range of 3.5 to 7.0.
Silky dogwood	Grows best on neutral spoil pH. Can withstand pH range of 4.5 to 7.0. Some value as wildlife food and cover plants. Poor surface protection.
Tatarian honeysuckle	Upright shrub, forms clumps. Does well on well-drained soils. Up to 12 ft tall. Takes 2 years for good cover.

Source: EPA, 1976, Vol. 1

- mulching application of straw, hay, wood chips, sawdust, dryback, bagasse (unprocessed sugar cane fibers), excelsior (fine wood shavings and manure) (EPA, 1982)
- chemical stabilization (including plastic films, latex emulsions, oil-in-water and resin-in-water emulsions).

Maintenance of the vegetated area may be necessary depending on the plant species selected. Maintenance includes mowing, removal of invader species, e.g. seedlings of deep-rooted trees, liming, fertilizing, replanting, and regrading.

Monitoring of a revegetated site is important to insure that the species of plants selected are adequately adapting to the site. Factors to be monitored include (Herman et al., 1976; Gilman et al., 1981):

- soil moisture
- soil aeration/oxygen content

- soil chemistry
- groundwater flow and chemistry
- plant condition

Special Precautions and Limitations

Temporary stabilization against erosion may be required while vegetation is being established. Techniques include:

- straw-bale check dams (for waterways)
- mulching application of straw, hay, wood chips, sawdust, dryback, bagasse (unprocessed sugar cane fibers), excelsior (fine wood shavings and manure) (EPA, 1982)
- chemical stabilization (including plastic films, latex emulsions, oil-in-water and resin-in-water emulsions).

3.3.7.4 Principal Data Requirements

Geography (suitability and selection)

- topography
- accessibility of vegetation
- vegetation characteristics

Soil characteristics (suitability and selection)

- type
- grain size distribution
- moisture content
- depth
- nutrient levels
- pH
- organic content

- waste concentrations

Climatology (suitability and selection)

- precipitation
- storm characteristics
- temperature

Infiltration (required function)

Surface water characteristics (suitability, selection, and required function)

- runoff
- flood characteristics
- chemistry
- drainage characteristics

Waste description(vegetation compatibility)

- chemical characteristics
- physical characteristics
- disposal practices

3.3.7.5 Elements of Cost Review

Components

Construction and Capital--

- seedbed preparation
- seed spreading
- vegetation used
- stabilizers

O & M--

- grass mowing
- refertilization

Major Factors

- vegetation availability
- vegetation requirements

Data

Unit costs for revegetation are given in Table 3-35.

Total costs for revegetating a 54,000 m^2 (520,500 ft^2) site using native grass, .6 meters (2 ft) of additional topsoil and mulching, in 1982 dollars, is $88,700 - 109,400 (SCS, 1980).

3.3.8 Seepage Basins and Ditches

3.3.8.1 Description

Seepage basins and ditches are used to discharge water collected from surface water diversions, groundwater pumping, or leachate treatment to groundwater. Both types discharge collected water to the groundwater by allowing it to seep through the ground. They usually have gravel-lined bases with sidewalls constructed of pervious material. There is considerable flexibility in designing seepage basins and ditches, but typically they will include a sediment trap with a bypass for excess flow, an emergency overflow, and the structure itself. Seepage basins are usually uncovered while seepage ditches most often are backfilled with topsoil. Water is introduced through a distribution line containing the sediment trap (EPA, 1982). A typical seepage basin is shown in Figure 3-20, and a typical seepage ditch is shown in Figure 3-21.

TABLE 3-35
UNIT COSTS FOR REVEGETATION

Description	1982 Unit Cost[a]
• Hydraulic spreading (hydroseeding), lime, fertilizer, and seed	\$600/acre
• Mulching, hay	\$180/acre
• Loam Topsoil, remove and stockpile on-site; using 200 h.p. dozer, 6' deep, 200' haul	\$ .97/yd^3
500' haul	\$3.71/yd^3
• Hauling loam on-site	\$2.36/yd^3
• Spreading loam, 4-6" deep	\$.51-.89/yd^3
• Plant bed preparation (unspecified), 18" deep, by machine	\$7.89/yd^3
• Hydraulic seeding and fertilization of large areas, with wood fiber mulch	\$.42/yd^2
• Mulch, hand spread 2" deep, wood chips	\$1.28/yd^2
• Liming slope areas	\$280/acre
• Fertilizing, level	\$250/acre
slope	\$340/acre
• Seeding, level	\$410/acre
slope	\$500/acre
• Jute mesh, stapled (erosion control)	\$.83/yd^2
• Sodding, in East, 1" deep, level	\$3.94/yd^2
slope	\$4.34/yd^2
• Maintenance:	
Grass mowing, slope	\$48/acre
level areas	\$22/acre
Refertilization	\$163/acre
Weeding/pruning shrubs	\$1,028/acre

TABLE 3-35

UNIT COSTS FOR REVEGETATION (Cont.)

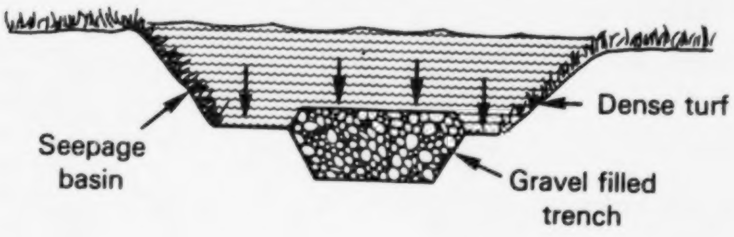
Description		1982 Unit Cost[a]
On-site planting		
• Trees, evergreens	30-36"	$56 ea.
	36-42"	$71 ea.
	42-48"	$101 ea.
	4-5'	$127 ea.
	5-6'	$165 ea.
Black Pines	7-8'	$165 ea.
Yews	2-2.5'	$42 ea.
Junipers	4-5'	$56 ea.
• Shade trees (balled and burlapped)		
	6-8'	$47 ea.
	8-10'	$66 ea.
	1.5-2.5" diam.	$178-279 ea.
	2.5-4.0" diam.	$445-635 ea.
Birch	8-10'	$99 ea.
Oak	8-10'	$107 ea.
• Shrubs (balled and burlapped)		
	2-3'	$23 ea.
	3-4'	$52 ea.
	4-5'	$64 ea.
Honeysuckle shrub	4-5'	$37 ea.

[a] All costs include materials and installation (labor and equipment), unless otherwise indicated. Note different units (acre; yd^2; yd^3; each).

Source: EPA, 1982

FIGURE 3-20

SEEPAGE BASIN: SHALLOW DEPTH TO GROUNDWATER
(Source: EPA, 1982)



3.3.8.2 Status

Conventional, demonstrated.

3.3.8.3 Feasibility and Effectiveness

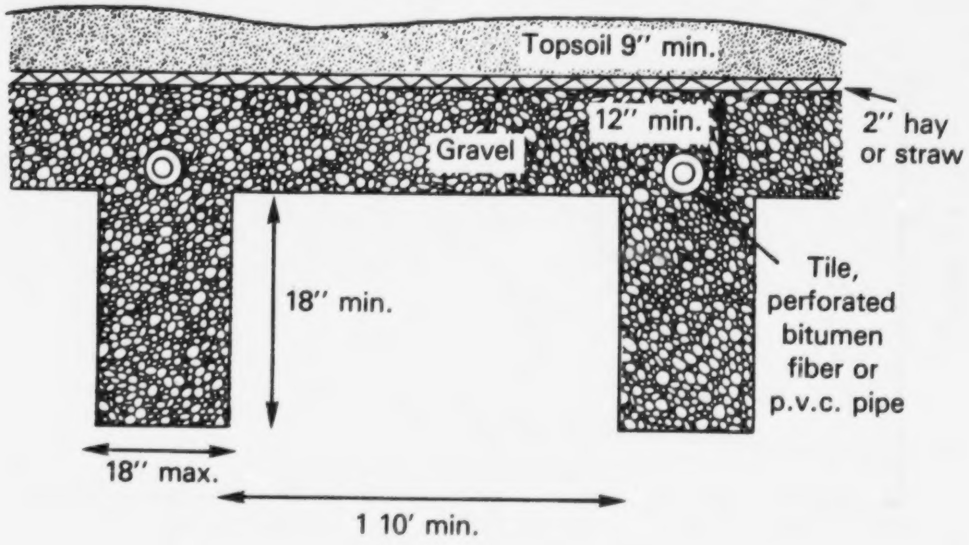
Lifetime

Seepage basins and ditches have a finite life and will ultimately become clogged with solids and biological growth. The loading rate which gives the largest, useful lifetime is called the long-term acceptance rate. The long-term acceptance rate is primarily a function of three factors (Healey and Laak, 1974):

1. The initial permeability of the surrounding soil as measured by the acceptance rate of clear water, m/min, under a hydraulic gradient of one.
2. The hydraulic gradient over the upper 5 cm (2 in.) of soil.
3. The loading pattern to be used (continuous or intermittent flooding).

FIGURE 3-21

SEEPAGE DITCH WITH INCREASED SEEPAGE EFFICIENCY
(Source: EPA, 1982)


Topsoil 9" min.
12" min.
Gravel
2" hay or straw
Tile, perforated bitumen fiber or p.v.c. pipe
18" min.
18" max.
1 10' min.

A plot of the long-term acceptance rate, adjusted to a hydraulic head of 0.3 meters (1 ft), versus soil permeability is given in Figure 3-22.

Design

Design of seepage basins and ditches is based on consideration of (Healey and Laak, 1974):

- the amount and quality of water to be discharged
- the permeability of the surrounding soil
- the highest elevation of the water table
- the depth to impermeable stratum

FIGURE 3-22

LONG-TERM ACCEPTANCE RATE OF EFFLUENT BY SOIL

(1 gpd/sq ft = 0.41 m/day; 1 fpm = 0.305 m/min)

(Source: Healy and Laak, 1974)

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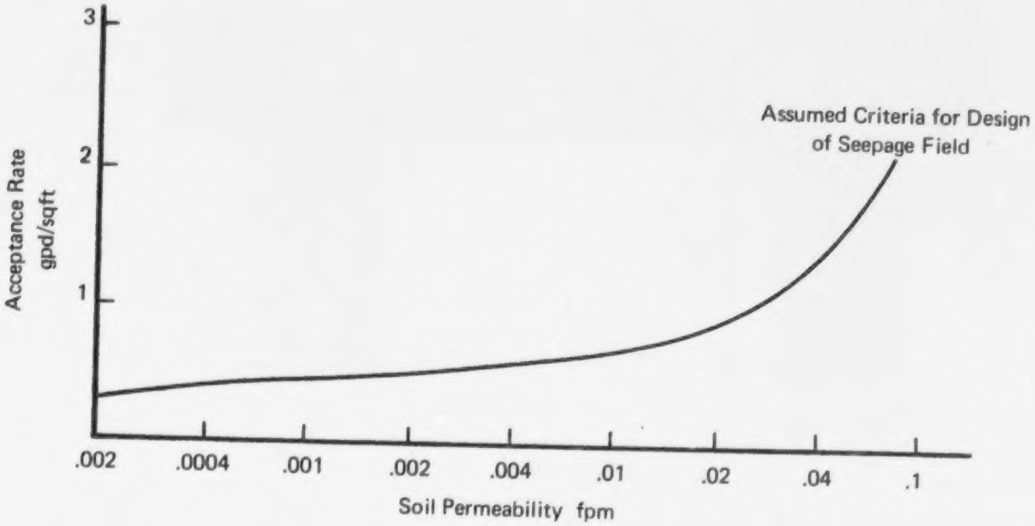


The specific relationship between these parameters depends on the combination of basins and ditches used in the seepage field.

Seepage Basins

Basin sidewalls should be made of pervious material. Gabions can be used for vertical sidewalls and dense turf for sideslopes. These also control erosion and slumping (EPA, 1982).

Infiltration can be improved in a basin by constructing gravel-filled trenches along the basin floor (EPA, 1982).

Seepage Ditches

Ditches are usually used in a parallel system. Important considerations for seepage ditches include (EPA, 1982):

- minimum depth -- 1.2 meters (3.9 ft)
- minimum spacing -- 3.0 meters (9.8 ft)
- maximum width -- 0.5 meters (1.6 ft)

The efficiency of seepage ditches can be improved by interconnecting adjacent ditches with a continuous gravel bed, as shown in Figure 3-21 (EPA, 1982).

Special Precautions and Limitations

None.

3.3.8.4 Principal Data Requirements

Depth to impermeable stratum (long-term acceptance rate)

Soil characteristics (lifetime)

- erosion potential (stabilization, sedimentation) (see discussion on erosion control in Section 2).
- permeability (long-term acceptance rate)
- hydraulic gradient in upper 5 cm of soil (long-term acceptance rate)

Storm characteristics (capacity)

Groundwater characteristics (long-term acceptance rate)

- depth to water table
- infiltration

Surface water characteristics (capacity, sedimentation)

- runoff
- drainage area
- sedimentation

Loading pattern (long-term acceptance rate, capacity)

3.3.8.5 Elements of Cost Review

Components

Construction and Capital--

- excavation
- gravel lining
- sediment trap

O & M--

- cleaning of sediment trap
- maintenance

Major Factors

- number and size of basins and ditches
- gravel

Data

Unit costs for seepage basins and ditches are similar to those of subsurface drains, given in Table 3-10.

3.4 SOIL AND WASTE TECHNOLOGIES

3.4.1 Excavation

3.4.1.1 Description

Excavation is accomplished by digging up waste or contaminated soil with either a dragline unit or a backhoe. As its name indicates, dragline equipment operates by dragging a bucket into the surface of the ground. The backhoe is a hydraulically-powered digging unit that can be mounted on tracked or wheeled vehicles.

3.4.1.2 Status

Conventional, demonstrated.

3.4.1.3 Feasibility and Effectiveness

Applicability

Dragline Units-- Effective for the removal of unconsolidated materials.

Backhoes-- Effective for the removal of compacted as well as loosely-packed materials. Backhoes offer more accurate digging bucket placement than the dragline. In addition, a specialized type of backhoe unit, called a Gradall^R, can be used to backfill and grade an excavation site or a drained surface impoundment. Backhoes are also capable of removing barrels when equipped with a sling or grappler for removing drummed waste.

Performance Characteristics

Digging depth and digging reach for a dragline unit and backhoe are dependent on the boom length. Values in Table 3-36 are based on a digging angle of 45 degrees. Other operating parameters include:

- optimum digging depth: 4.5 meters (15 ft)
- maximum digging depth:
    1. Dragline: 18 meters (60 ft)(EPA, 1982)
    2. Backhoe: 21 meters (70 ft)(ASCE, 1982)
- theoretical production rates (see Table 3-37)

TABLE 3-36

EXCAVATION EQUIPMENT CHARACTERISTICS

Excavation Equipment	Hoe or Bucket Size (Cubic Meters)	Typical Digging Reach (Meters)	Typical Digging Depth (Meters)
Drag-line crane unit	.8 (1 cubic yard)	14 (45 feet)	5 (16 feet)
	1.3 (1 3/4)	17 (57)	7 (24)
	1.5 (2)	21 (68)	9 (30)
Backhoe	.8 (1)	11 (35)	7 (22)
	1.5 (2)	15 (49)	9 (30)
	2.7 (3 1/2)	21 (70)	14 (45)

Source: EPA, 1982

Design Equations

The following two methods for designing excavation plans are traditionally used:

1. Cross Sectional Method

Volume of material to be removed is calculated by averaging the cross sectional area between successive cross cuts (average end areas) and multiplying by the distance between the cuts as follows (Davis, Foote, and Kelly, 1966):

$$V = \frac{L}{2} (A_1 + A_2)$$

where:

V = volume of a section (ft^3)

L = distance between end areas (ft)

A_1, A_2 = end cut cross sectional areas (ft^2)

TABLE 3-37
PRODUCTION RATES FOR EXCAVATION EQUIPMENT

Excavation Equipment	Soil Type	Bucket Size (Cubic Meters)	Production Rate[a] (Cubic Meters/Hour)
Drag-line crane unit	Moist loam	.8 (1 cubic yard)	99 (130 cubic yard/hour)
	Sandy clay	1.5 (2)	168 (220)
	Hard dense	.8 (1)	69 (90)
	Clay	1.5 (2)	122 (160)
Backhoe	Moist loam	.8 (1)	65 (85)
	Sandy clay	1.5 (2)	134 (175)
	Hard dense	.8 (1)	50 (65)
	Clay	1.5 (2)	99 (130)

[a] based on typical operating conditions

Source: EPA, 1982

Formula is only exact when $A_1 = A_2$ but is generally a good approximation when the two values are not equal.

A second cross-sectional formula is the prismodal formula (Davis, Foote, and Kelly, 1966):

$$V = L/6 \ (A_1 + 4 \ A_m + A_2)$$

where:

V = volume of a section (ft^3)
L = distance between end areas (ft)
A_1, A_2 = area of end cross section (ft^2)
A_m = area of cross section midway between the two ends (ft^2)

Using the prismodal formula, A_m is determined by averaging the linear dimensions of the end cross sections.

2. Contour Method

Volume calculation utilizes horizontal cross sections taken directly from a contour map. The volume of a section to be removed is calculated as follows (Smith, 1976):

$$V = CI \left(\frac{C_1 + C_2}{2}\right)$$

where:

V = volume of earthwork (ft^3)
CI = contour interval (ft)
C_1, C_2 = areas of adjacent closed contours (ft^2)

If the contour interval CI is uniform throughout the earthwork area, then the total volume can be calculated as follows (Smith, 1976):

$$V = CI \left(\frac{C_1}{2} + C_2 + C_3 + \ldots C_{L-1} + \frac{C_L}{2}\right)$$

where:

V = total volume (ft)
C_1 = area of first contour (ft^3)
C_L = area of last contour (ft^2)
CI = contour interval

When contour information is available in sufficient detail, the contour method is considered to be quicker, more versatile, and more accurate than the cross-sectional method (Smith, 1976).

Special Precautions and Limitations

Field personnel must be protected from accidental exposure to buried wastes.

3.4.1.4 Principal Data Requirements

topography (volume)

accessibility of equipment (implementability and cost)

soil characteristics (equipment suitability)

- compaction
- strength properties (sufficient to support equipment)
- depth

waste description (safety plan)

- chemical characteristics
- physical characteristics
- disposal practices

3.4.1.5 Elements of Cost Review

Components

Construction and Capital--

- excavation
- reburial

O & M--

- transportation

Major Factors

- volume
- reburial location

Data

Unit costs are presented in Table 3-38.

Costs for excavating and transporting 596,388 cubic meters of waste and soil with reburial at a landfill 20 miles away is approximately $42 million (1982 dollars). Ninety percent of this total is due to reburial (tipping fees) at a secure landfill (SCS, 1980).

3.4.2 Drum Handling

3.4.2.1 Description

Drum handling addresses the handling and/or consolidation of drummed waste before it is trucked to an off-site facility or stored for on-site treatment. After excavation, drums are generally transported to an on-site staging area for processing and/or removal. Waste samples are then taken and analyzed, and incompatible drums are segregated to prevent accidents in the staging area. If a drum is in poor condition, the contents are transferred to an alternate drum or the drum is overpacked prior to transport. Pre-transport consolidation of drummed liquid waste is achieved by pumping waste from drums into a mixing tank or directly into a tank truck. Drummed solids and sludges are generally consolidated in waste trailer units. Empty drums are crushed and disposed of on or off-site.

3.4.2.2 Status

Conventional, demonstrated; but waste consolidation capabilities will vary greatly from site to site.

3.4.2.3 Feasibility and Effectiveness

General Features

Careful drum handling is necessary whenever drummed waste is found at a site. Transport of drummed waste in original, overpacked, or alternate drums is most applicable when the number of drums at the site is low. Pre-transport consolidation of waste is most applicable when there is a large number of drums at a site in poor condition, since the consolidation of large quantities of waste

TABLE 3-38
UNIT COSTS FOR EXCAVATION

Excavation using dragline	3/4 yd^3 bucket, 90° swing, Rating 35 yd^3/hr	\$2.62/yd^3
	1.5 yd^3 bucket, 90° swing, Rating 65 yd^3/hr	\$1.77/yd^3
Excavation using backhoe	Hydraulic, crawler mounted	
	- 1 yd^3 bucket, rating 45 yd^3/hr	\$2.26/yd^3
	- 1.5 yd^3 bucket, rating 60 yd^3/hr	\$1.92/yd^3
	- 2 yd^3 bucket, rating 75 yd^3/hr	\$2.02/yd^3
	- 3.5 yd^3 bucket, rating 150 yd^3/hr	\$1.47/yd^3
	Wheel mounted	
	- 0.5 yd^3 bucket, rating 20 yd^3/hr	\$4.11/yd^3
	- 0.75 yd^3 bucket, rating 30 yd^3/hr	\$3.15/yd^3
Excavation using clamshell	0.5 yd^3 bucket, rating 20 yd^3/hr	\$4.41/yd^3
	1 yd^3 bucket, rating 35 yd^3/hr	\$2.95/yd^3

Source: EPA, 1982

can be more cost-effective than overpacking and transporting many barrels.

Special Precautions and Limitations

Violent reaction and release of hazardous constituents of reaction products is possible. It is, therefore, important that the waste from each drum or drum lot be analyzed to prevent the mixing of incompatible waste. A mixing tank can be used as a precaution to prevent an accident once the waste is loaded into a tank truck.

Compatibility of waste materials is a major concern in storing and/or consolidating waste. To minimize risk of mixing incompatible wastes, the following storage compatibility categories have been developed by the US EPA Environmental Response Team (Turpin, et al., 1981):

- caustic (non-flammable)
- caustic (flammable)
- acid (non-flammable)
- acid (flammable)
- oxidizer (non-flammable)
- oxidizer (flammable)
- radioactive

3.4.2.4 Principal Data Requirements

Waste Description (consolidation, safety)

- pH
- flammability
- water reactivity
- redox potential
- volatility
- radioactivity
- physical characteristics
- drum location and condition
- waste compatibility for mixing

3.4.2.5 Elements of Cost Review

Components

Construction and Capital--

- excavation
- metered pumps
- mixers
- storage and consolidation tanks

O & M--

- repacking of failed drums

Major Factors

- analysis of drum contents
- condition of drums
- quantity of waste

Data

Available cost data are limited. Costs reported for a New Jersey storage site were 1.5 million dollars to remove 10,000 drums before a fire at the site, and 17 million dollars to remove 25,000 drums (a second contractor) after the fire (Finkel andd Golob, 1981). Analysis costs for priority pollutants is on the order of $1,000/sample.

3.4.3 Encapsulation

3.4.3.1 Description

Encapsulation is the process by which wastes are enclosed in a stable, water resistant material. Wastes may be bound in a polymer matrix prior to encapsulation. A typical process, developed by the TRW Corporation (TRD 6), binds dried waste with 1, 2-polybutadiene (a polymer matrix) and then jackets it with a 1/4 inch-thick layer of high density polyethylene. The encapsulated waste can then be landfilled.

3.4.3.2 Status

Developmental for dried waste and drums; conceptual for sludges.

3.4.3.3 Feasibility and Effectiveness

General

Encapsulated wastes provide stable containment for dried inorganic wastes or secondary containment for drummed waste. The method may be suitable for containing low volumes of toxic waste. However, necessary equipment may not be suitable for transport to remedial action sites.

Laboratory testing results indicate that for a finite period of time encapsulated wastes have excellent mechanical, chemical and biological integrity and are capable of withstanding impacts and freeze-thaw stresses (EPA, 1982). Long-term integrity has yet to be demonstrated. More detailed information is not available.

Special Precautions and Limitations

Not available.

3.4.3.4 Principal Data Requirements

- accessibility of equipment (implementibility, cost)
- waste description - organic or inorganic (feasibility, applicability)
- types
- form - dried, sludge, drum

3.4.3.5 Elements of Cost Review

Components

Construction and Capital--

- dewatering
- encapsulation equipment
- landfill

O & M--

- volume
- physical characteristics of waste

Major Factors

- process development (status)

Data

None available.

3.4.4 Dewatering

3.4.4.1 Description

Dewatering can be either passive or active. Passive dewatering techniques require no mechanical energy or additional thermal energy inputs for the removal of water. Water is removed through evaporation and free (or gravity) drainage. For a discussion of active dewatering, see "Filtration."

3.4.4.2 Status

Conventional, demonstrated.

3.4.4.3 Feasibility and Effectiveness

General

Passive dewatering techniques are only applicable when the material is free-draining, or when the evaporation potential at the site is high. If toxic volatile compounds are present in the sludge, escape of these compounds into the atmosphere should be considered.

Passive techniques include:

- Stockpiling. Material is placed in a drained area to allow free drainage. Material can then be taken from the top of the stockpile and spread in thin layers in a drying area to allow the remaining water to evaporate (TRD 7).
- Temporary sand-drying beds. Material is placed in small diked containment areas with a surface layer of coarse sand underlain by layers of graded gravel. The beds have an earthen (preferably clay) bottom which slopes to underdrains. Dewatering is by gravity drainage and evaporation (EPA, 1982).

Special Precautions and Limitations

The feasibility of passive evaporative dewatering depends on the evaporation potential at the site. The evaporation potential is the maximum evaporation that can be expected under ideal conditions. It is defined as the difference between the normal annual Class A pan evaporation rate (found by standard testing) and the average annual precipitation. A positive evaporation potential (e.g., 136 inches/year in the Sonora Desert represents a maximum value) indicates significant solar evaporation and a suitability for passive drying. A negative evaporation potential (e.g., -70 inches/year in the Pacific Northwest Coast represents a minimum value) indicates the need for active dewatering techniques (TRD #7). Passive dewatering may be possible in some areas with a negative evaporation potential if the waste is covered. This strategy is employed for sludge drying in the Northeast United States.

3.4.4.4 Principal Data Requirements

Climatology (suitability of passive dewatering)

- precipitation
- evapotranspiration (normal annual Class A pan evaporation rate)
- wind characteristics
- temperature
- exposure to direct sunlight

Waste Description (suitability for dewatering)

- water content
- sediment size
- thermal stability
- odor
- presence of volatile toxics
- drainage ability (free draining)

3.4.4.5 Elements of Cost Review

Components

Construction and Capital--

- excavation

O & M--

- none

Major Factors

- volume
- excavation requirements

Data

None available.

3.5 AIR CONTROL TECHNOLOGIES

3.5.1 Pipe Vents

3.5.1.1 Description

A pipe vent is a vertical or lateral perforated pipe installed at a site to collect gases or vapors. It is usually surrounded by gravel to prevent clogging. Pipe vents can discharge to a treatment system or directly to the atmosphere. Discharge can be natural (atmospheric) through either mushroom or "U" shaped tops, or forced by means of a negative pressure fan. Pipe vents are used to prevent the migration and release to the atmosphere of volatile toxics and other dangerous gases. Typical pipe vent configurations are given in Figure 3-23.

3.5.1.2 Status

Conventional, undemonstrated. Pipe vents have been used primarily in the control of methane at municipal landfills. Application to uncontrolled hazardous waste sites has been extremely limited and technology effectiveness is unclear.

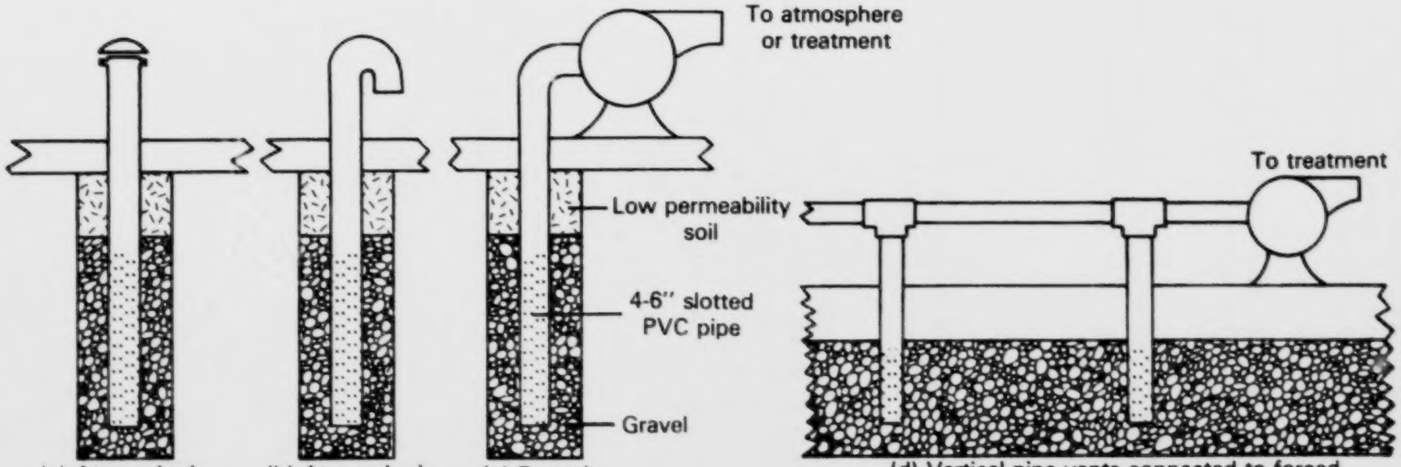
3.5.1.3 Feasibility and Effectiveness

Construction (EPA, 1982)

Pipe vents are constructed in the same manner as groundwater monitoring well.

FIGURE 3-23

DESIGN CONFIGURATION OF PIPE VENTS
(Source: EPA, 1982)


To atmosphere
or treatment
To treatment
Low permeability
soil
4-6" slotted
PVC pipe
Gravel

(a) Atmospheric vent Mushroom Top

(b) Atmospheric vent "U" Top

(c) Forced Ventilation

(d) Vertical pipe vents connected to forced ventilation manifold system

Pipe vents may be installed with a gravel pack to prevent clogging, although there is some debate as to whether this is necessary (Rovers, et al., 1978). The gravel pack should be sealed from the atmosphere with cement, cement/soil grout, or clay.

Vent depth should extend to the bottom of the fill or contaminated material, but not below the water table or into liquid waste.

Vents will be more effective when used in conjunction with a surface seal to prevent uncontrolled gas release.

Vent Placement

Atmospheric vents should be placed at contours of maximum gas concentration, (determined by a gas probe).

Spacing of forced vents depends on the radius of influence of the pipe (discussed below). Test drawdowns to measure head loss as a function of distance from the vent, at various pumping rates may be performed to determine spacing at a specific site.

Typical vent spacing is 17 meters (56 ft).

Radius of Influence

Radius of influence of a forced vent depends on pipe characteristics:

- pumping rate;
- intake depth; and
- pipe diameter.

Site characteristics:

- cover material;
- depth of fill; and

- soil permeability.

Figure 3-24 shows how the radius of influence varies with pumping rate and depth of intake.

Selection of Vent Type

The decision of whether to use forced or atmospheric ventilation depends on vapor flux (the amount of gas migrating to the air). If the rate of vapor flux is higher than can be safely vented to the atmosphere, forced ventilation may be required. The following equations can be used for determining vapor flux:

$$J = D_o \left(P_a^{10/3} / P_t^{2}\right) (C_2 - C_s)/L$$

where:

J = vapor flux from soil surface ($ng/cm^2/day$)

D_o = vapor diffusion coefficient of volatilizing material

P_a = soil air-filled porosity (cm^3/cm^3)

P_t = total soil porosity (cm^3/cm^3)

C = concentration of the volatilizing material at the surface of the soil ($\mu g/l$)

C_s = concentration of the volatilizing material at the bottom of soil layer ($\mu g/l$)

L = soil depth (cm)

and:

$$C_s = pm/RT$$

where:

p = vapor pressure of volatilizing material (mm Hg)

m = molecular weight of a compound (g/mole)

R = molar gas constant (mm Hg/°K mole)

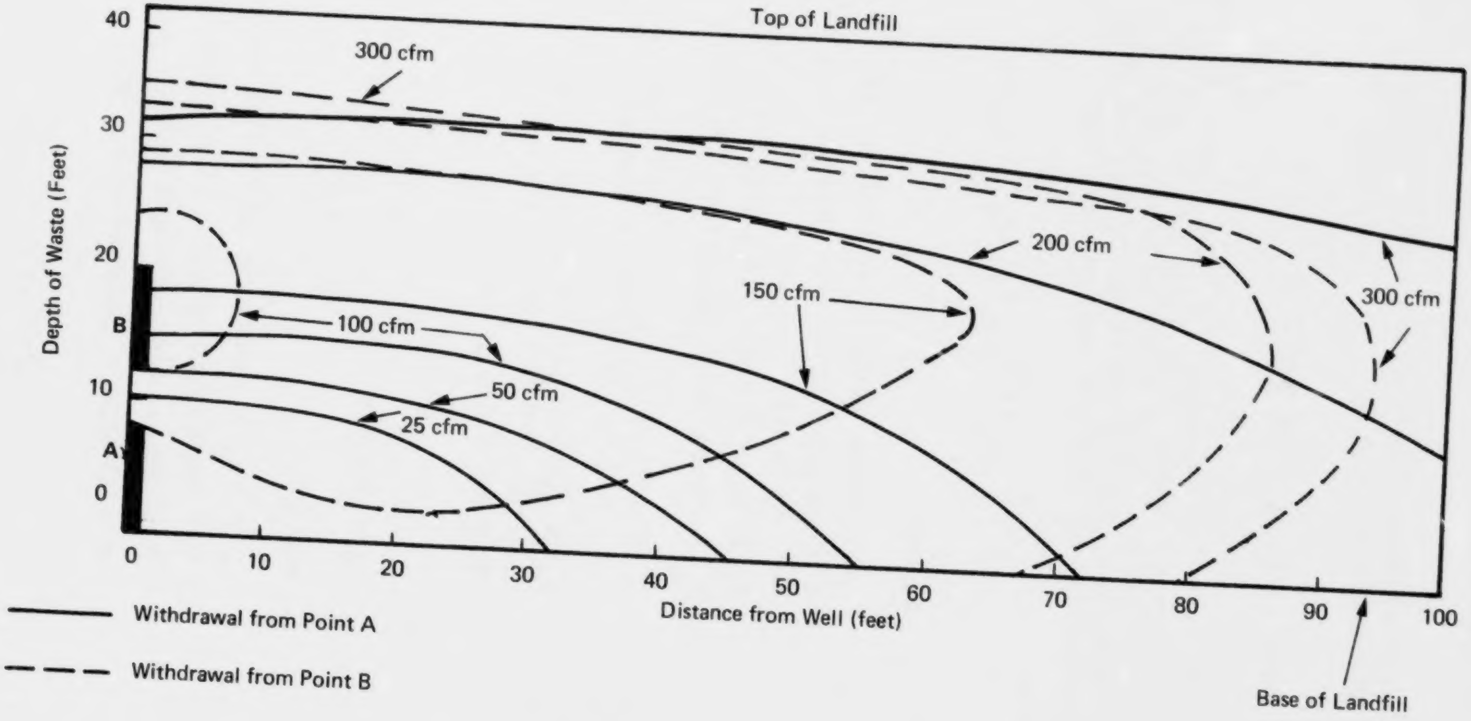
T = absolute temperature (°K)

FIGURE 3-24

RADIUS OF INFLUENCE OF PIPE VENT

(for one inch water pressure at different withdrawal rates)

(Source: Carlson, 1977)



If the diffusion coefficient is not known for a given substance or at a given temperature, it can be estimated (assuming that the vapor pressures for substances A and B are low) by the following equations:

$$D_A = D_B (M_B/M_A)^{1/2}$$

where:

D_A = diffusion coefficient of substance A

M_A = molecular weight of substance A

D_B = diffusion coefficient of substance A

M_B = molecular weight of substance B

and:

$$D_2 = D_1 (T_2/T_1)^{1/2}$$

where T = absolute temperature (°K).

More rigorous equations for estimating diffusivity are given in Shen and Toffelmire, 1980 and Thibodeaux, 1979.

Special Precautions and Limitations

None.

3.5.1.4 Principal Data Requirements

Soil characteristics (radius of influence, vapor flux)

- permeability
- porosity - air-filled and total
- depth

Temperature (vapor flux)

Depth to water table (vent placement)

Waste description

- physical characteristics
- disposal practices

Gas concentrations (vent placement)

Cover characteristics (vent placement, radius of influence)

Vapor flux (vent type: forced or atmospheric)

3.5.1.5 Elements of Cost Review

Components

Construction and Capital--

- piping and laterals
- installation
- fan (for forced system)

O & M--

- power for forced system
- monitoring

Major Factors

- number and size of pipes
- length and size of laterals
- type of system (forced or atmospheric)

Data

Unit costs asociated with pipe vents are given in Table 3-39.

Total costs for a forced pipe vent system at a disposal site are given in Table 3-40.

3.5.2 Trench Vents

3.5.2.1 Description

A trench vent is a narrow trench backfilled with gravel forming a path of least resistance through which gases migrate upward to the atmosphere or to a collection manifold. These vents typically surround the waste site or span a section of the perimeter of the waste site. By diverting the flow in this way, the trench vents form a barrier against lateral migration of methane or toxic vapors. Trench vents are often lined on one side to form an effective barrier against gas migration. They can be open or capped with clay and fitted with collection laterals and riser pipes vented into the atmosphere. They can also be connected to a negative pressure fan or blower. Various configurations of trench vents are shown in Figure 3-25.

3.5.2.2 Status

Conventional, undemonstrated. Trench vents have been used primarily in the control of methane at municipal landfills. Application to uncontrolled hazardous waste sites has been extremely limited and technology effectiveness is unclear.

3.5.2.3 Feasibility and Effectiveness

Construction

Maximum trench depth is 3 meters (10 ft)(EPA, 1982).

Trench performance can be enhanced by:

TABLE 3-39
UNIT COSTS OF PIPE VENT COMPONENTS

Fans (a) Flow Rate (cfm)	Total Installed Cost (1982 dollars)	Annual Operating Cost (1982 dollars)
0-136 @ 3" H_2O	689	85 (2)
135-600 @8" H_2O	1,568 - 1,641	60 - 390
500-2000 @ 8" H_2O	2,128 - 2,296	60 - 1,314
1900-6000 @ 8" H_2O	4,676 - 5,225	190 - 3,940

	Total Installed Costs ($/ft)			
	4"	6"	8"	10"
Pipe				
PVC	15.19	21.09	--	--
Asbestos Bonded	1.64	2.19	3.36	5.12
Galvanized Iron	22.00	43.10	56.60	75.00
Elbows				
PVC	22.20	46.90	82.30	163.50
Galvanized Iron	38.10	87.00	160.40	234.10
ABS	19.10	30.60	38.80	93.30
Tees				
PVC	31.40	58.50	119.50	239.70
Galvanized Iron	60.00	136.90	267.80	451.00
ABS	19.10	30.60	42.40	93.10
Butterfly Valves				
Cast Iron	326.00	479.70	725.70	1039.40
PVC	162.40	268.80	425.60	560.00
Flow Meters	996.30	1254.60	1445.30	--

---

[a] Belt-driven, utility mount, weather cover, and corrosion resistant coating.

[b] Cost = Fan Brake HP x 0.746 $\frac{KW}{HP} \times \frac{8760\ hr}{yr} \times \frac{\$0.04}{KW\text{-}hr}$

Source: EPA, 1982

TABLE 3-40
COSTS FOR A FORCED PIPE VENT SYSTEM

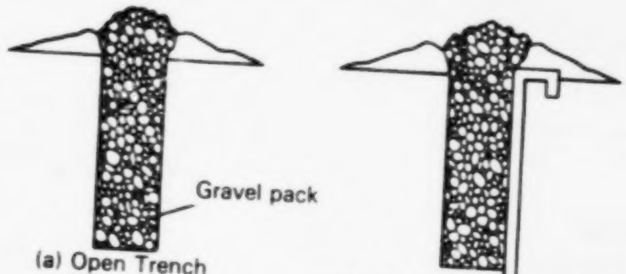
Basis:
- A collection system in which a blower is connected to pipe vents.
- All manifold components are sized for 0.15 m (6 in) piping diameters.
- Costs include installation.

	Total Unit $ (1982 dollars)	
Capital Costs	Lower U.S.	Upper U.S.
Blower 1,250 cfm (2 hp)	1,240	2,090
PVC Pipe: Risers (300 m) 4 in.	7,020	12,950
Laterals (910 m) 8 in.	43,400	75,130
PVC Pipe Tees 8 in. (25)	2,650	4,390
Butterfly Valves 8 in. (5)	1,190	2,020
Flow Meter 8 in. (1)	730	1,520
PVC Pipe Elbows 8 in. (25)	1,880	2,830
Moisture Traps (10)	3,760	6,380
Monitoring Program		
Monitoring Equipment	560	560
Monitoring Wells, Gas (32)	850	1,680
Capital Costs (subtotal)	63,280	109,550
Overhead Allowance (25 percent)	15,820	27,390
Contingency Allowance (30 percent)	18,980	32,870
Total Capital Costs	98,080	169,810
O&M Costs		
Monitoring 24 hr per time, 24 times per year (96 hr/yr) (labor costs)	890	1,870
Power Cost 1.5 kWh @2 hp = 12,900 kWh/yr (0.04/kWh) (8,600 hr/yr operation)	520	520
Operating Cost 40 hr/mo (480 hr/yr	5,950	12,340
Total O&M Costs	7,360	14,730

Source: SCS, 1981

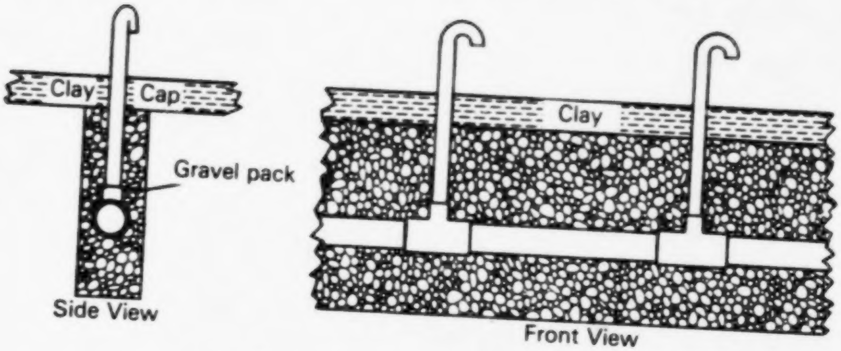
FIGURE 3-25

DESIGN CONFIGURATION OF TRENCH VENTS
(Source: EPA, 1982)

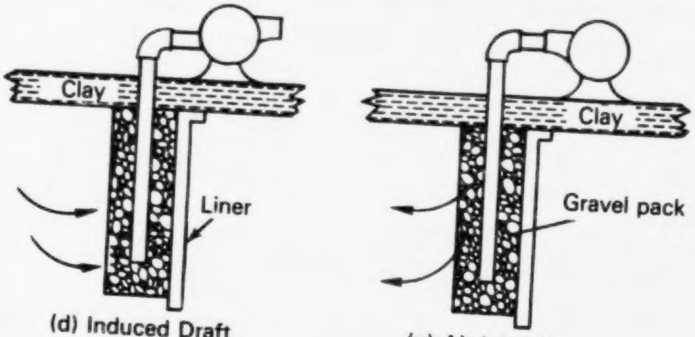

Gravel pack

(a) Open Trench

(b) Open Trench with Liner


Clay
Cap
Gravel pack
Side View
Clay
Front View

(c) Closed Trench with Lateral and Risers


Clay
Liner
Clay
Gravel pack

(d) Induced Draft

(e) Air Injection

- lining one side of the trench with an impermeable barrier to prevent migration through and past the trench;
- extending trenches to form a continuous seal with groundwater or impermeable stratum to prevent migration underneath the trench;
- installing laterals and riser pipes to facilitate gas movement. A typical riser spacing is 15 meters (49 ft); and
- covering the site with a surface seal to increase the effectiveness of the trench as the path of least resistance.

Selection of Vent Type

The equation for determining vapor flux are given in the discussion of pipe vents.

Special Precautions and Limitations

Trenches should not be located in an area of low relief to prevent water infiltration and clogging with solids. A slope can be constructed along the trench to keep runoff from infiltrating. This is of particular importance for trench vents which are not capped but open to the atmosphere.

3.5.2.4 Principal Data Requirements

Topography (vent placement)

Soil characteristics (radius of influence, vapor flux)

- permeability
- porosity (air-filled and total)
- depth

Temperature (vapor flux)

Depth to water table (vent placement)

Waste description (vent placement)

- physical characteristics

- disposal practices

Gas concentrations (vent placement)

Cover characteristics (vent placement, radius of influence)

Vapor flux (vent type: forced or atmospheric)

3.5.2.5 Elements of Cost Review

Components

Construction and Capital--

- trench excavation
- liner
- laterals and riser pipes
- gravel
- backfill
- blower (for forced system)

O & M--

- power for blower
- monitoring

Major Factors

- number, length and depth of trenches
- length and size of laterals and riser pipes
- type of system (forced or atmospheric)
- liner material

Data

Unit costs associated with trench vents are given in Table 3-41.

Total cost for a trench vent system are given in Table 3-42.

TABLE 3-41
UNIT COSTS FOR TRENCH UNITS

	Basics	Costs (1982 dollars)
Trench excavation	20' deep, 4' wide, by backhoe	\$1.27/cubic yard
Spread excavated material	Spread nearby and grade and cover trench	\$0.84/cubic yard
Well-point dewatering	500' header, 8" diameter, for one month	\$95/linear foot
Gravel	Buy and haul from pit 2 miles, backfill with dozer	\$9.65/cubic yard
Sheet piling	Pull and salvage	\$7.24/square foot
Walers, connections, struts	2/3 salvage	\$130/ton^2
Lateral with risers	12" corrugated polyethylene lateral, 6" PVC risers, 15' long every 50'. 500' lateral	\$8.26/linear foot
Liner	Hypalon (36 mil) Bracketed with heavy-weight geotextile fabric	\$2.35 - 3.36/square foot
	4" gunite layer with mesh	\$5.88 -10.67/square foot

Source: EPA, 1982

TABLE 3-42
COSTS OF TRENCH VENTS FOR A DISPOSAL SITE

Basis:
- Use of lateral risers and a synthetic liner.
- Well point dewatering done for one month.
- Laterals with risers: Laterals 0.3 m (12 in) PVC; risers 0.15 m (6 in) PVC pipe by 7 m long, placed every 15 m along the lateral.
- Liner consists of hypalon (36 mil) bracketed with heavyweight geotextile fabric.

	Total Unit Cost (1982 dollars)	
Capital Costs	Lower U.S.	Upper U.S.
Trench Excavation (4,255 m^3) 935 m (L) x 3.5 m (d) x 1.3 m (w)	6,850	7,790
Spread Excavated Material (2,850 m^3)	2,200	2,600
Gravel (2,850 m^3)	22,690	35,030
Pipe, PVC: 12" Lateral (950 m) Riser Pipe, 6" (450 m)	137,600	195,630
Liner (5,700 m^2)	30,030	50,830
Backfill (1,405 m^3)	2,990	3,580
Monitoring Program		
Monitoring Equipment	600	600
Monitoring Wells, Gas (32) (1/2" PVC, 3.6 m deep)	920	1,800
Capital Costs (subtotal)	203,880	297,860
Overhead Allowance (25 percent)	50,970	74,470
Contingency Allowance (20 percent)	40,780	59,570
Total Capital Costs	295,630	431,900
O&M Costs		
Monitoring 24 times/yr (4 hr/time) (96 hr/yr)(labor costs)	880	1,870

Source: SCS, 1981

SECTION 4

TREATMENT TECHNOLOGIES

4.1 INTRODUCTION

This section contains discussions of individual or groups of closely related leachate treatment technologies. Each discussion follows the format described in Section 1.

The selection of treatment technologies depends in part on the chemical nature of the leachates or wastes being treated as well as on many other factors. Table 4-1 displays the relative treatability of 17 classes of hazardous constituents by the various technologies described in this Section. As an example of the treatability of hazardous waste leachates, Table 4-2 classifies EPA's 129 priority pollutants into the 17 classes. Table 4-1 can be used to suggest which treatment technologies may be appropriate for leachates containing these pollutants.

In addition, Table 4-3 summarizes the many data requirements common to the treatment technologies. The individual technology discussions may expand on this table or incorporate additional data needs.

4.2 BIOLOGICAL TREATMENT

4.2.1 Activated Sludge

4.2.1.1 Description

In the activated sludge process bacteria breaks down organic wastes in aqueous streams by oxidation and hydrolysis in the presence of oxygen (aerobically). The microorganisms become acclimated

TABLE 4-1

TREATMENT PROCESS APPLICABILITY MATRIX

TREATMENT TECHNOLOGY	Alcohols	Aliphatics	Amines	Aromatics	Ethers	Halocarbons	Metals	PCB	Pesticides	Phenols	Phthalates	Polynuclear Aromatics	Cyanide	Ammonia	Total Dissolved Solids	Total Suspended Solids	Grease and Oil
Biological Treatment	E	V	V	V	G	P	P,F	N	N,P	G	G	N,P	F,G	G,E	N		
Activated Sludge	E	V	V	V	G	P	P,F	N	N,P	G	G	N,P	F,G	G,E	N		
Rotating Biological Disc	E	V	V	V	G	P	P,F	N	N,P	G	G	N,P	F,G	G,E	N		
Trickling Filter	E	V	V	V	G	P	P,F	N	N,P	G	G	N,P	F,G	G,E	N		
Surface Impoundment	E	V	V	V	G	P	P,F	N	N,P	G	G	N,P	F,G	G,E	N		
Land Treatment	E	V	V	V	G	P	P,F	N	N,P	G	G	N,P	F,G	G,E	N		
Chemical Treatment	E	V	V	V	G	P	P,F	N	N,P	G	G	N,P	F,G	G,E	N		
Chemical Oxidation	E	V	V	V	G	P	P,F	N	N,P	G	G	N,P	F,G	G,E	N		
Alkaline Chlorination	N	N	N	N	N	N	N	N	N	N	N	N	E	N	N		
Ozonation	G,E	P	N	F,G		F,G			E	E		G	E		N		
Chemical Reduction	N	N	N	N	N	N	G	N	N	N	N	N	N	N	N		
Neutralization	-	-	-	-	-	-	-	PH	CONTROL		-	-	-	-	-	-	-
Precipitation				F			E				G	R	N	N	N		
Ion Exchange							E							N	E		
Wet Air Oxidation	X	X	X	X	X	X			X	X	X		X		N		
Physical Treatment																	
Carbon Adsorption	V	V	V	G,E	V	G,E	N,P	E	E	E	E	G,E	N	N	N		
Density Separation																	
Sedimentation																X	
Flotation																	X
Filtration																X	
Reverse Osmosis	V	V		V			E		E	V					E		
Stripping							N						N	G	N		
Equalization/Detention	-	-	-	-	-	-	PRETREATMENT			-	-	-	-	-	-	-	-
In-Situ Treatment																	
Biological Methods	X	X	X	X	X					X	X						
Chemical Methods							X						X				

Source: TRD 5

KEY

E = Excellent Performance Likely

G = Good Performance Likely

F = Fair Performance Likely

P = Poor Performance Likely

R = Reported to be Removed

N = Not Applicable

V = Variable Performance Reported for Different Compounds in the Class

X = Treatment is Applicable but Not Specified in the Source Reference

- A Blank Indicates No Data Available

TABLE 4-2

TREATABILITY CLASSIFICATION OF THE 129 PRIORITY POLLUTANTS

NAME	TREATABILITY CLASS	SYNONYMS
Acenaphthene	Aromatics	1,2-Dihydroacenaphthylene
Acenaphthylene	Aromatics	
Acrolein	Misc.	2 Propenal
Acrylonitrile	Misc.	2 Propenenitrile
Aldrin	Pesticides	
Anthracene	Aromatics	
Antimony	Metals	Stibium
Arsenic	Metals	
Asbestos	Misc.	Amianthus
Beryllium	Metals	
Benzene	Aromatics	Benzol
Benzidine	Substitute Aromatics	
Benzo (a) Anthracene	Aromatics	
3,4-Benzofluoranthane	Aromatics	
Benzo (k) Fluoranthane	Aromatics	
Benzo (ghi) Perylene	Aromatics	
Benzo (e) Pyrene	Aromatics	
e-BHC-Alpha	Pesticides	
b-BHC-Beta	Pesticides	
r-BHC (Lindane)-Gamma	Pesticides	
g-BHC-Delta	Pesticides	
bis(2-chloroethoxy)Methane	Chlorinated Ethers	

TABLE 4-2

TREATABILITY CLASSIFICATION OF THE 129 PRIORITY POLLUTANTS (Cont.)

NAME	TREATABILITY CLASS	SYNONYMS
bis(2-chloromethyl)Ether	Chlorinated Ethers	
bis(Chloromethyl)Ether	Chlorinated Ethers	
bis(2-Chlorolsopropyl)Ether	Chlorinated Ethers	
bis(2-Ethylaxyl)Phthalate	Phthalate Esters	
Bromoform	Chlorinated Alkanes	Tribromomethane
4-Bromophenyl Phenyl Ether	Chlorinated Ethers	
Butyl Benzyl Phthalate	Phthalate Esters	
Cadmium	Metals	
Carbon Tetrachloride	Chlorinated Alkanes	Tetrachloromethane
Chlordane	Pesticides	
Chlorobenzene	Chlorinated Aromatics	Monochlorobenzene
Chlorodibromomethane	Chlorinated Alkanes	
Chloroethane	Chlorinated Alkanes	
2-Chloroethyl Vinyl Ether	Chlorinated Ethers	(2-Chloroethoxy)Ethane
Chloroform	Chlorinated Alkanes	Trichloromethane
2-Chlorophenol	Phenols	
4-Chlorophenyl Phenyl Ether	Chlorinated Ethers	
2-Chlorophythalene	Chlorinated Aromatics	
Chromium	Metals	
Chrysene	Aromatics	1,2-Benzphenanthrene
Copper	Metals	
Cyanide	Miscellaneous	
4,4-DDD	Pesticides	

TABLE 4-2
TREATABILITY CLASSIFICATION OF THE 129 PRIORITY POLLUTANTS (Cont.)

NAME	TREATABILITY CLASS	SYNONYMS
4,4-DDE	Pesticides	
4,4-DDT	Pesticides	
Dibenzo (a,h)Anthracene	Chlorinated Aromatics	
1,3-Dichlorobenzene	Chlorinated Aromatics	
1,4-Dichlorobenzene	Chlorinated Aromatics	
3,3-Dichlorobenzidene	Substituted Aromatics	
Dichlorbromothane	Chlorinated Alkanes	
Dichlorodiflurometha ne	Chlorinated Alkanes	
1,1-Dichloroethane	Chlorinated Alkanes	
1,2-Dichloroethane	Chlorinated Alkanes	
1,1-Dichloroethylene	Chlorinated Alkanes	
2,4-Dichloro Phenol	Phenols	
1,2-Dichloropropane	Chlorinated Alkanes	
1,2-Dichloropropylene	Chlorinated Alkanes	
Dieldrin	Pesticides	
Diethyl Phthalate	Phthalate Esters	
2,4-Dimethyl Phenol	Phenols	
Dimethyl Phthalate	Phthalate Esters	1,2-Benzenedicarboxylic Acid
Di-N-Butyl Phthalate	Phthalate Esters	
4,6-Dinitro-O-Cresol	Phenols	2-Methyl-4, 6-Dinitrophenol
2,4-Dinitrophenol	Phenols	Aldifen
2,4-Dinitrotoluene	Substituted Aromatics	
2,6 Dinitrotoluene	Substituted Aromatics	

TABLE 4-2

TREATABILITY CLASSIFICATION OF THE 129 PRIORITY POLLUTANTS (Cont.)

NAME	TREATABILITY CLASS	SYNONYMS
Di-N-Octyl Phthalate	Phthalate Esters	
1,2-Diphenyl Hydrazine	Substituted Aromatics	
A-Endosulfan-Alpha	Pesticide	
B-Endosulfan-Beta	Pesticide	
Endosulfan Sulfate	Pesticide	
Endrin	Pesticide	
Endrin Aldehyde	Pesticide	
Ethylbenzene	Aromatics	
Fluoranthene	Aromatics	
Fluorene	Aromatics	
Haphthalene	Aromatics	
Heptachlor	Pesticides	
Heptachlor Epoxide	Pesticides	
Hexachlorobenzene	Chlorinated Aromatics	Perchlorobenzene
Hexachlorobutadiene	Chlorinated Alkanes	
Hexachlorocyclopentadiene	Chlorinated Alkanes	
Hexachloroethane	Chlorinated Alkanes	
Indeno (1,2,3-c,d)Pyrene	Aromatics	
Isophorone	Miscellaneous	
Lead	Metals	
Mercury	Metals	Hydrargyrum

TABLE 4-2
TREATABILITY CLASSIFICATION OF THE 129 PRIORITY POLLUTANTS (Cont.)

NAME	TREATABILITY CLASS	SYNONYMS
Methyl Bromide	Chlorinated Alkanes	Bromomethane; Monobromomethane; Embafume
Methyl Chloride	Chlorinated Alkanes	Chloromethane
Methylene Chloride	Chlorinated Alkanes	Dichloromethane
Nickel	Metals	
Nitrobenzene	Substituted Aromatics	Nitrobenzol
2-Nitrophenol	Phenols	Nitrobenzol
4-Nitrophenol	Phenols	
N-Nitrosodimethylamine	Miscellaneous	
N-Nitrosodi-N-propylamine	Miscellaneous	
N-Nitrosodiphenylamine	Miscellaneous	
Para-Chloro-Meta-Cresol	Phenols	
PCB-1016	Polychlorinated Biphenyls	
PCB-1221		
PCB-1232		
PCB-1242		
PCB-1248		
PCB-1254		
PCB-1260		
Pentachlorophenol	Phenols	Penta; PCP; Penchloro; Santophen

TABLE 4-2
TREATABILITY CLASSIFICATION OF THE 129 PRIORITY POLLUTANTS (Cont.)

NAME	TREATABILITY CLASS	SYNONYMS
Phenanthane	Aromatics	
Phenol	Phenols	Carbolic Acid; Phenic Acid
Pyrene	Aromatics	Benzo(def)Phenanthrene
Selenium	Metals	
Silver	Metals	
2,3,7,8-Tetrachlorodlbenzo-P-Dioxin		
1,1,2,2-Tetrachloroethane	Chlorinated Alkanes	
Tetrachloroethylene	Chlorinated Alkanes	Perchlorothylene; Ethylene Tetrachloride
Thallium	Metals	
Toluene	Aromatics	Methylbenzene
1,2-Trans-Dichloroethylene	Chlorinated Alkanes	
1,2,4-Trichlorobenzene	Chlorinated Aromatics	
1,1-Trichloroethane	Chlorinated Alkanes	
1,1,2-Trichloroethane	Chlorinated Alkanes	Vinyl Trichloride
Trichloroethylene	Chlorinated Alkanes	Trichloroethene; Ethinyl Trichloride
Trichlorofluoromethane	Chlorinated Alkanes	Fluorotrichloromethane
2,4,6-Trichlorophenol	Phenols	Dowicide 25; Omal
Vinyl Chloride	Chlorinated Phenols	Chloroethylene
Zinc	Metals	

Source: TRD 5

TABLE 4-3

TREATMENT TECHNOLOGY DATA REQUIREMENTS

TREATMENT TECHNOLOGY	Volume	TKN	Flow	pH	Acidity Expressed as $CaCO_3$ Equivalent	BOD	COD	TOC	TSS	TDS	Metals	Cyanide	Temperature	Complexing Agents	Viscosity	Climate	Soil Permeability	Soil CEC	Oxidation Reduction Potential	Leachate Variability	Phosphorus Content	Particle Size of Suspended Solids	Presence of Interfering Species
Biological Treatment																							
Activated Sludge	X	X	X	X	X	X	X	X	X		X	X	X			X				X	X		X
Rotating Biological Disc	X	X	X	X	X	X	X	X	X		X	X	X			X				X	X		X
Trickling Filter	X	X	X	X	X	X	X	X	X		X	X	X			X				X	X		X
Surface Impoundment	X	X	X	X	X	X	X	X	X		X	X	X			X				X	X		X
Land Treatment	X	X	X	X	X	X	X	X	X		X	X	X			X	X	X		X	X		X
Chemical Treatment																							
Chemical Oxidation																							
Alkaline Chlorination	X		X	X	X							X											
Ozonation	X		X	X																			
Chemical Reduction	X		X	X							X												
Neutralization	X		X	X	X																		X
Precipitation	X		X	X					X	X	X	X		X									X
Ion Exchange	X		X	X					X	X	X	X											X
Wet Air Oxidation	X		X	X				X															X
Physical Treatment																							
Carbon Adsorption	X		X	X				X	X	X					X					X			X
Density Separation																							
Sedimentation	X		X	X					X													X	
Flotation	X		X	X					X													X	
Filtration	X		X	X					X													X	X
Reverse Osmosis	X		X	X					X	X					X					X			X
Stripping	X		X	X																			
Equalization/Dentention	X		X																	X			
In-Situ Treatment																							
Biological Methods	X		X	X		X	X	X					X			X	X	X					X
Chemical Methods	X		X	X							X					X	X	X					X

to the wastewater environment through continuous recycle as shown in Figure 4-1.

A sludge residue is generated along with the treated effluent. As shown, the operation includes an aeration basin, a clarifier, and provisions for returning a portion of the sludge from the clarifier to the aeration basin. Aeration systems typically release air into the system, but pure oxygen may also be used. Generally, equalization, neutralization, and/or primary sedimentation precede activated sludge processing. Disposal options for the sludge include landfill, incineration, and land application.

4.2.1.2 Status

Conventional, demonstrated. Existing activated sludge treatment plants have been used to treat leachate from hazardous waste facilities.

4.2.1.3 Feasibility and Effectiveness

Performance of an activated sludge treatment system is typified by BOD removal efficiency. In hazardous waste applications removal efficiency of specific compounds or classes of compounds may be a more important measure of performance. The mean BOD removal efficiency for 92 industrial wastewater streams which were studied by the USEPA was 86 percent EPA, 1980). The mean influent and effluent BOD levels were 1310 and 184 mg/1 respectvely. Units are typically designed to remove 85 to 95 percent of a wastewater BOD load and are capable of treating BOD levels up to 10,000 mg/1.

Performance depends primarily on the type of organics present (see treatability summary), type of aeration, and retention time. Aeration methods are summarized in Table 4-4.

For effective operation, influent to an activated sludge system must be at a pH level near neutral, and process loading must be consistent. Usually an equalization tank and a pH adjustment system are pretreatment steps.

4.2.1.4 Design Basis

Key design parameters are (Adams and Eckenfelder, 1974):

FIGURE 4-1
TYPICAL ACTIVATED SLUDGE SYSTEM
(Source: ADL, 1976)

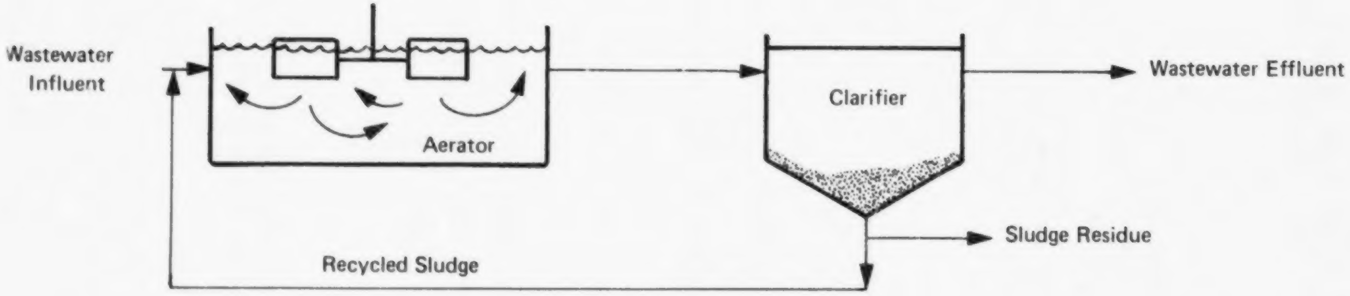

Wastewater Influent
Aerator
Clarifier
Wastewater Effluent
Sludge Residue
Recycled Sludge

TABLE 4-4
SUMMARY OF AERATION METHODS

Method	Description	Application
Extended Aeration	Longer wastewater retention times in the aeration basin.	Low organic loading and reduced sludge quantities desired.
Pure Oxygen Aeration	Wastewater aeration with pure oxygen in a closed aeration tank.	High organic and/or metal loading.
Contact Stabilization	Aeration of recycled sludge on its return to the aeration tank.	Sludge removes BOD rapidly by biosorption. Contact stabilization decomposes the sorbed organics.

- BOD removal rate, Sr (primary design target)

$$Sr = (S_o - S_e)\ (8.34)Q$$

Where:

S_o = influent total BOD (mg/l)
S_e = target effluent soluble BOD (mg/l)
Q = average flow (mgd)

- Detention time

Detention time is the longer of the following two calculations, depending on the controlling mechanism:

$$t = \frac{S_o(S_o - S_e)}{KX_vS_e} \quad \text{(BOD is the controlling factor)}$$

$$t = \frac{S_o}{(X_v)(F/M)} \quad \text{(F/M is the controlling factor)}$$

where:

K = removal rate coefficient (1/day)

X_v = average mixed liquor volatile suspended solids (MLVSS)

F/M = food to microorganism ratio (lb organics/lb MLVSS/day), obtained by laboratory tests as shown below

Oxygen requirements should be calculated based on summer operating conditions when oxygen demand is usually highest and transfer efficiency lowest. The oxygen requirement equation is:

$$R_r = a'(S_o - S_e)\ b'x\ X_v + R_c + R_n$$

where:

R_r = oxygen utilization (lb O_2/day)

a' = oxygen utilization coefficient for synthesis (lb O_2 utilized/lb organics removed)

b' = oxygen utilization coefficient for endogenous respiration (lb O_2 utilized/lb MLVSS)

x = biodegradable fraction of MLVSS

R_c = chemical oxygen demand (lb/day)

R_n = oxygen utilized for ammonia to nitrate conversion

The horsepower required to meet the oxygen demand is calculated by:

$$hp = \frac{\text{lb } O_2\text{/day}}{(N)(24\text{hr/day})}$$

where N is the oxygen transfer efficiency. "N" can be calculated as follows (Adams and Eckenfelder, 1974):

$$N = N_o \left[\left(\frac{BC_{sw} - C_L}{C_s} \right) \alpha \Theta T_w - 20 \right]$$

where:

N_o = standard oxygen transfer efficiency at 20°C, standard pressure for tap water containing no oxygen (lb O_2/(hr)hp)

B = ratio of dissolved oxygen in a saturated waste solution to that in tap water (usually .92-.98)

C_{sw} = dissolved oxygen saturation concentration in waste (mg/l)

C_L = design dissolved oxygen concentration (mg/l)

C_s = dissolved oxygen concentration in pure water at 20% and standard pressure (mg/l)

α = ratio of oxygen transfer rate in waste to that in pure water

Θ = temperature coefficient (1.02 for diffused aeration, 1.028 and for surface aeration)

T_w = aeration basin temperature (°C)

Horsepower requirements can also be estimated from the following rough relationship:

$$hp = \frac{\text{BOD removed per day}}{\text{45 lb BOD removed per hp-day}}$$

A minimum of 100 hp per mgd is required to insure solid suspension in the reactor tank.Food to microorganism ratio (F/M)

Food is the biodegradable portion of the leachate. There is a particular F/M ratio at which settleability is optimum. This optimum ratio must be determined experimentally by measuring both effluent suspended solids and zone-settling velocity as a function of F/M and plotting the results on a single graph (Adams and Eckenfelder, 1974). This value is used in the design, unless BOD controls retention time (see above), in which case:

$$F/M = \frac{S_o}{X_v t}$$

- Clarifier design

Clarifier design depends either on the hydraulic loading or on the solids flux. Design surface area (A) for the clarifer should be the larger of the areas given by the following equations (Adams and Eckenfelder, 1979):

$$A = \frac{Q_1}{O.R.}$$

$$A = \frac{(Q_2 + R)\ 8.34\ Xv}{\text{solids flux}}$$

Where:

$O.R. = K(ZSV)(Fc)$

and:

Q_1 = flow (gpd)

Q_2 = flow (mgd)

O.R. = clarifier overflow rate (gpd/ft^2)

R = sludge recycle rate (mgd)

Xv = average aeration basin MLVSS (mg/l)

solids flux = solids loading ($lb/ft^2/day$)

K = constant ($180(gpd/ft^2)/(ft/hr)$)

ZSV = zone settling velocity (ft/hr)

Fc = scale up factor

Nutrient requirements

Activated sludge requires phosphorus and nitrogen nutrients, to sustain biological activity. Nutrient requirements are calculated as follows (Adams and Eckenfelder, 1974):

$$\text{lb Nitrogen required/day} = \frac{0.123\ X\Delta X_v}{0.77} + 0.07\ \frac{(0.77-X)\Delta X_v}{0.77}$$

$$\text{lb Phosphorous required/day} = \frac{0.026X\Delta X_v}{0.77} + 0.01\ \frac{(0.77-X)\Delta X_v}{0.77}$$

where:

X = biodegradable fraction of MLVSS

Nitrogen and phosphorus in the influent can provide some of the nutrient requirements.

- Sludge production can be calculated by (Adams and Eckenfelder, 1974):

$$\text{Total Sludge} = f\ X_i + \Delta X_v - X_e$$

where:

f = nonbiodegradable fraction of the influent suspended solids

X_i = influent suspended solids (lb/day)

ΔX_v = excess biological sludge production (lb/day)

X_e = effluent suspended solids (lb/day)

Special Precautions and Limitations

Some heavy metals and some organics at concentration above a few ppm are toxic to activated sludge organisms. (See EPA, 1982 for threshold toxicity concentrations for some metals.) If toxic species are present in sufficiently high concentrations, pre-treatment process must be incorporated into the treatment flow to remove them. Activated sludge may have difficulty in removing refractory organics (i.e., highly chlorinated organics) from wastewater.

4.2.1.5 Principal Data Requirements

Kinetic parameters (treatability, see Adams & Eckenfelder, 1974)

- specific BOD reaction rate coefficient (for retention time)
- oxygen coefficients (for oxygen requirements)
- sludge coefficients (biodegradable fraction)
- biodegradable sludge fraction (nutrient requirements)
- oxygen transfer coefficient (horsepower)
- standard oxygen transfer efficiency (horsepower)
- oxygen saturation coefficient (horsepower)
- temperature correction coefficient (retention time, horsepower)

Average and maximum influent flow (retention time)

Influent temperature (horsepower)

Ambient extreme ambient temperature, summer and winter (horsepower)

Average and maximum influent BOD (retention time)

Influent suspended solids (sludge production)

Non-biodegradable fraction of influent solids (sludge production)

Influent nitrogen and phosphorous (nutrient requirements)

Average MLVSS - generally assumed to be between 2,000 and 4,000 (retention time)

4.2.1.6 Elements of Cost Review

Components

Construction and Capital--

- excavation

- tanks
- pumps
- clarifier
- aeration equipment

O & M--

- chemicals
- electricity
- solids disposal

Major Factors

- process size
- aeration requirements
- detention time

Data

A unit cost example is presented in Table 4-5.

4.2.2 Surface Impoundments

4.2.2.1 Description

Surface impoundments (also called lagoons) are systems in which the processes of microbial oxidation, photosynthesis, and sometimes anaerobic digestion combine to breakdown hazardous organic compounds. They are similar to activated sludge units without sludge recycle. Aeration may be supplied passively by wind and algae or, in aerated surface impoundments, by mechanical aerators. The oxygen introduced by aeration is used by the bacteria to oxidize organic matter to carbon monoxide (CO_2); the algae use the CO_2 for photosynthesis and produce more oxygen. The ecology of surface impoundments closely resembles a natural eutrophic lake, a more complex system than other biological treatment systems. A secondary benefit of

TABLE 4-5
ESTIMATED UNIT COSTS OF ACTIVATED SLUDGE SYSTEMS

Activated Sludge

Basis: 1×10^6 gallons/day, 10,000 ppm COD, 4,000 ppm BOD, 6,000 ppm MLVSS, 365 day/year operation/sludge management costs not included

Estimated Capital Investment: $3,078,000

	Annual Quantity	Cost Per Unit Quantity, 1982 $	Annual Cost, 1982 $
Variable Costs			
Operating Labor	8,760 MH	19.60/MH	171,700
Maintenance (4% of Inv.)			123,120
Quick-Lime	400 tons	31.00/ton	12,400
Ammonia	330 tons	210.00/ton	69,300
Phosphoric Acid	180 tons	520.00/ton	93,600
Electricity	5.3×10^6 kWh	.04/kWh	212,000
Total Variable Costs			682,100
Fixed Costs			
Taxes and Insurance (2% of Inv.)			61,560
Capital Recovery (10 Years @ 10%)			503,820
Total Fixed Costs			565,380
Total Costs			1,247,500
Unit Cost ($/$10^3$ gal)			3.42

Source: ADL, 1976

surface impoundments is clarification. Physical and chemical treatment processes may also be carried out in surface impoundments.

Figure 4-2 shows a flow diagram of an aerated impoundment, with a secondary clarifier. A separate clarifier may not be required with other impoundment designs, e.g., facultative impoundments, if the design includes a separate baffled settling compartment, two or more impoundments in series, or other special features.

4.2.2.2 Status

Conventional, demonstrated.

4.2.2.3 Feasibility and Effectiveness

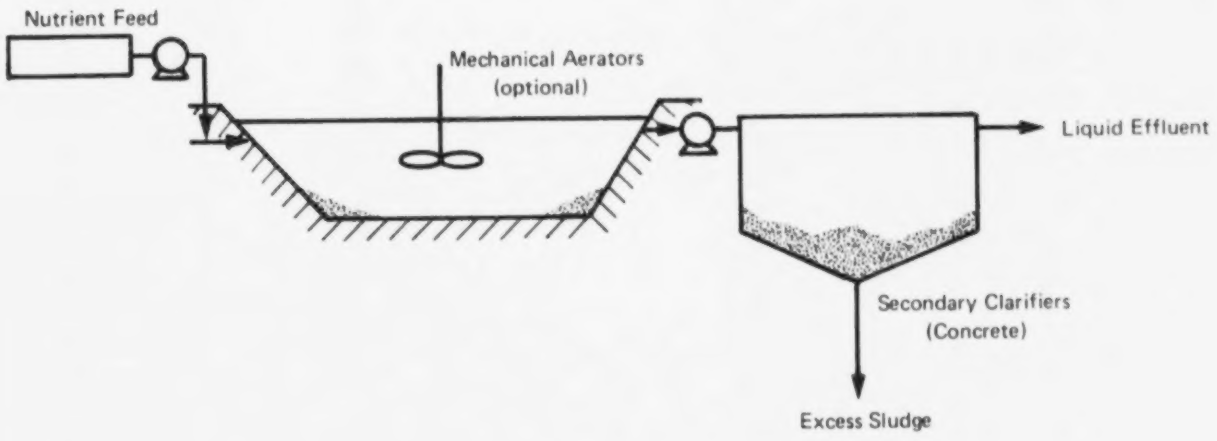
General Features

The types of surface impoundments most commonly used are as follows:

Type	Description
● Aerated Impoundment	Mechanical or diffused aeration using impoundments 1.8-6.1 m deep. Forced flow in oxidation ditch an alternative. Only aerobic action allowed. Usually requires a separate clarifier.
● Facultative Impoundment	No forced aeration. Degradation is via both aerobic (near surface) and anaerobic (near bottom) processes. Depths are typically .6-1.5 m.
● Waste Stabilization Ponds (Aerobic Surface Impoundments)	No forced aeration, however, impoundment is kept aerobic by natural processes (wind, algal activity). Depth is generally .3-.6 m.

FIGURE 4-2

AERATED SURFACE IMPOUNDMENT
(Polymeric Lined Earth Construction)
(Source: ADL, 1976)


Nutrient Feed
Mechanical Aerators
(optional)
Liquid Effluent
Secondary Clarifiers
(Concrete)
Excess Sludge

• Anaerobic Surface Impoundments	Impoundment uses a lower surface-to-volume ratio to increase the anaerobic action. This allows (and requires) higher organic loadings than with other types. Less sludge is generated. Operating Temperatures above ambient (∿25-30°C) are usually required.

Surface impoundments can normally handle BOD levels of 200-500 mg/l; anaerobic systems can tolerate somewhat higher levels. For wastes with BOD levels in this range and with suspended solids less than 0.1 percent, impoundments may be used as the primary method of BOD removal. Removal efficiencies for BOD are usually in the range of 60-90 percent. More often, impoundments are used to polish low BOD content effluent from activated sludge or trickling filters prior to discharge.

High performance has been demonstrated for (TRD 5):

- alcohol
- amines
- cyanides
- phenols
- phthalates

Variable performance has been observed for (TRD 5):

- aliphatics
- amines
- aromatics

Poor performance has been observed for (TRD 5):

- halocarbons
- metals
- pesticides

- polynuclear aromatics (PNA)

Surface impoundments are unsuited for (TRD 5):

- total dissolved solids
- PCBs

Special Precautions and Limitations

- Shock Loadings--Impoundments are very sensitive to shock loadings of toxic chemicals; leachate may need equalization or pretreatment in some cases.
- Temperature Effects:--Impoundments are most efficient during warm weather (about 30 degrees C); cold weather or ice formation will significantly reduce efficiency and require longer detention times.
- Suspended Solids--To reduce excess sludge removal requirements, the influent concentration of suspended solids should be kept below about 0.1 percent for stabilization ponds and 1.0 percent for aerated impoundments.
- Gas Generation and Chemical Volatilization--Anaerobic activity will generate methane and hydrogen sulfide. Volatile chemicals will easily be transferred to the air. Offensive odors and/or unacceptable human exposures may result. An estimate of such volatilization losses may be required.
- Sludge Removal--Provisions must be made for the periodic removal and disposal of excess sludge.

4.2.2.4 Design Basis (from Fair, et al., 1968; Adams and Eckenfelder, 1974; and Hammer, 1975).

The primary design parameters to be set are:

1. The type, number and configuration of impoundments to be used.

2. The detention time (which is related to influent and effluent pollutant concentrations, degree of removal, temperature and the nature of the wastes).

3. The depth (and surface area) of the impoundment.

4. The sludge generation rate.

Secondary design parameters may be associated with the need for mechanical aeration pretreatment (for removal of toxics and suspended solids or equalization), and a final clarification step.

Type, number, configuration, and design of these parameters will generally be determined from considerations of: (a) the nature (including strength, composition) of the wastes; (b) the volume flow rate to be treated (including likely variations in this flow); (c) the land area available; (d) effluent limitations and the implied removal efficiencies; (e) the local meteorology (temperatures, insolation, rainfall); and (f) costs. A design for a surface impoundment should explicitly state how these factors were considered in the selection of the proposed design.

Design details should cover construction details, such as impoundment bed, use of liners, dike slopes, freeboard, inlet and outlet structures, connections between impoundments, access for (and means of) sludge removal, and overflow protection.

Detention time (see Table 4-6) provides a summary of the range of detention times (and other design parameters) associated with various types of surface impoundments. For removal of BOD, COD, TOC, the detention time may be derived from:

$$t = \left(\frac{S_o - S_e}{S_e}\right) \frac{X}{k}$$

where:

t = detention time (days)

S_o = influent total BOD, COD, TOC (mg/l)

S_e = effluent soluble BOD, COD or TOC (mg/l)

X = average or equilibrium concentration of VSS in impoundment (mg/l)

k = specific organic removal rate coefficient (l/mg·day)

Other equations for t are available (e.g., Fair et al., 1968) which may be more appropriate in some cases than the one provided above. A proposed design should clearly indicate how the detention time was estimated and justify all assumptions and key inputs (e.g., X , k) used in the calculations.

In some cases it may be desirable to estimate the oxygen requirements, the food-to-microorganism ratio, nutrient requirements; and, if mechanical aeration is used, the energy requirements. Equations for these parameters are given in the discussion on Activated Sludge.

The depth of water in the impoundment will be determined primarily by the type of impoundment selected. (See Table 4-6.) Land availability and meteorology may be secondary factors.

The required surface area (SA) of the impoundment may then be roughly estimated from:

$$\text{SA (m}^2\text{)} = \frac{\text{Flow (m}^3\text{/d)} \cdot \text{Detention time (t)}}{\text{Depth (m)}}$$

A larger land area will be required than the area obtained from the equation above since the equation assumed vertical walls and did not consider the area required for the surrounding dike and access areas.

It is necessary to estimate a sludge generation rate in order to properly design any clarifier that may be used, e.g., with an aerated impoundment, or to plan for periodic removal of excess sludge from other impoundments where the sludge settles in situ. An equation for estimating excess sludge production is provided in the discussion on Activated Sludge.

TABLE 4-6

TYPICAL VALUES OF DESIGN PARAMETERS FOR SURFACE IMPOUNDMENTS

	Facultative	Anaerobic	Aerobic	Aerated
Depth (m)	0.6 - 1.5	2.4 - 6.1	0.3 - 0.6	1.8 - 6.1
Organic Load (kg BOD/km^2/d)	1,100 - 11,000	25,000 - 225,000	10,000 - 22,000	1,100 - 33,000
Detention Time (days)	7 - 30	30 - 50	2 - 6	3 - 10
Influent BOD Concentration (mg/l)	200 - 500	500 and up	200	200 - 500

Source: ADL, 1976

4.2.2.5 Principal Data Requirements

Kinetic Parameters (treatability studies). Same as for activated sludge (viz), except biodegradable sludge fraction not required.

Other Data--generally same as for activated sludge. Non-biodegradable fraction and average MLVSS not required.

Summer and winter ambient conditions (minimum detention time)

- temperature
- wind velocity
- insolation - solar radiation
- relative humidity

4.2.2.6 Elements of Cost Reviews.

Components

Construction and Capital--

- excavation
- construction materials
- pumps
- mixers

O & M--

- electricity
- chemicals

Major Factors

- excavation requirements
- process size
- impoundment lining material

Data

A cost example (unit and total costs) is given for an aerated impoundment Table 4-7. Costs for an anerobic lagoon will be higher than an aerated lagoon if the process is operated at elevated temperatures. A cost example for an anerobic digestor is given in Table 4-8.

4.2.3 Rotating Biological Discs

4.2.3.1 Description

A rotating biological disc (RBD) is a fixed film biological method of treating effluent containing organic waste, similar in operating principle to trickling filters. A series of discs (2-3 meter diameter), or drums in some configurations, coated with a microbial film, rotate at 0.5-15 rev/min through troughs containing the effluent. 40-50 percent of the disc surface area is immersed in the effluent; the uncovered portion of the disc exposes the microbial film to the atmosphere during each rotation out of the trough. The shearing motion of the disc through the effluent keeps the biological floc from becoming too dense. The discs are usually arranged in series in groups of four. The process can be used for roughing, secondary treatment and nitrification. A schematic of a RBD is shown in Figure 4-3 (EPA, 1982).

4.2.3.2 Status

Conventional, undemonstrated (for leachate).

4.2.3.3 Feasibility and Effectiveness

TABLE 4-7

COST ESTIMATES FOR AERATED SURFACE IMPOUNDMENTS

Basis: - 1 x 10^6 GPD; 10,000 ppm COD; 4,000 ppm BOD; 90% Removal--
30,034 lb/day BOD; 365 day/yr operation

Estimated Capital Investment: $1,828,500

	Annual Quantity	Cost Per Unit Quantity, 1982 $	Annual Cost, 1982 $
Variable Costs			
Operating Labor	8,760 MH	19.60/hour	171,700
Maintenance (4% of Inv.)			73,100
Quicklime	400 tons	31.00/ton	12,000
Electricity	5.35 x 10^6kWh	.04/kWh	214,000
Ammonia	330 tons	210.00/ton	69,000
Phosphoric Acid	180 tons	520.00/ton	94,000
Total Variable Costs			633,800
Fixed Costs			
Taxes and Insurance (2% of Inv.)			36,600
Capital Recovery (10% - 10 years)			297,300
Total Fixed Costs			333,900
Total Annual Costs			967,700
Unit Cost ($/$10^3$ Gal)			2.65

Source: ADL, 1976

TABLE 4-8
OPERATING COST ESTIMATES FOR ANAEROBIC DIGESTION SYSTEM

Basis: - 100,000 GPD; 5% solids - 365 days/yer; 0.5 lbs volatile solids per cubic foot of digestor capacity per day.

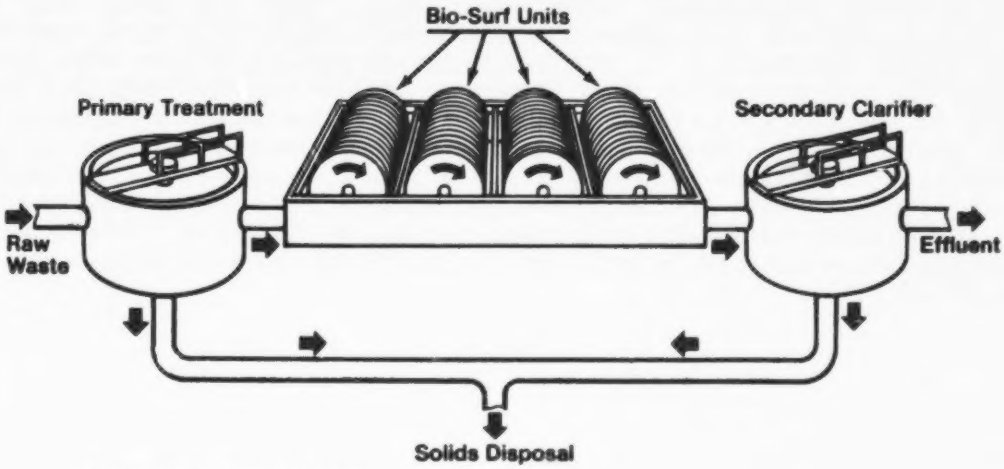
Estimated Capital Investment: $2,025,000

	Annual Quantity	Cost Per Unit Quantity, 1982 $	Annual Cost, 1982 $
Variable Cost			
Operating Labor	8,760 MH	19.60/hour	171,700
Maintenance (4% of Inv.)			81,000
Quicklime	200 tons	31.00	6,000
Electricity	450 x 10^3 kWh	.04/kWh	18,000
Total Variable Costs			276,700
Fixed Costs			
Taxes and Insurance (2% of Inv.)			40,500
Capital Recovery (10%-10 yrs.)			314,300
Total Fixed Costs			354,800
Total Costs			631,500
Unit Cost ($/$10^3$ gal)			17.30

Source: ADL, 1976

FIGURE 4-3

ROTATING BIOLOGICAL DISC TREATMENT SCHEMATIC
(Source: ADL, 1976)



General Features

As indicated in the schematic, RBD typically requires both primary treatment and secondary clarification. A large treatment system may combine several modular RBD units in a number of parallel trains with each train containing units in series.

A RBD process should be capable of treating the same type of wastes as an activated sludge or aerated impoundment process. BOD removal efficiencies should also be comparable. Key features of RBDs which may differentiate them are the characteristic modular construction, ease of operation, good settleability of solids flushed from the disc surfaces, low hydraulic head loss, and shallow excavation which make it adaptable to new or existing treatment facilities. In addition, enclosed (covered) systems may be used to provide some protection against low temperatures (EPA, 1980; Hammer, 1975).

RBDs are considered to be more reliable than other fixed bed processes because they withstand hydraulic and organic surges more effectively. Also, they do not plug up in the manner that trickling filters may (Metcalf and Eddy, 1979).

Special Precautions and Limitations

Like other biological treatment units, RBDs are sensitive to temperature changes and removal efficiencies will fall with temperatures below 20 degrees C. Enclosed units will provide some protection, but condensation (and freezing of the condensate) may be a problem in very cold periods. High organic loadings may result in septic conditions in the first stage, and supplemental aeration may be required. Use of dense media for early stages may result in media clogging (EPA, 1980). In addition, as with activated sludge organisms, the biological media are sensitive to pH and some toxic metals and organisms which may be present in leachate from hazardous waste disposal sites.

4.2.3.4 Design Basis

The primary design parameters to be set are:

- the number and configuration of RBDs to be used;
- the detention time of the wastes in the chambers;
- the rotational velocity of the media; and
- the sludge generation rate.

Secondary design parameters may be associated with the pre- and post-treatment units, the possible need for supplemental aeration in the first stages, the possible need for nutrient addition and covers, and the specific design of the discs to be used.

Table 4-9 provides a summary of typical values or ranges for several design parameters that are applicable to industrial or municipal wastewater treatment.

Number and Configuration

The comments provided in the discussion on Surface Impoundments are applicable here and are not repeated.

TABLE 4-9
DESIGN CRITERIA FOR ROTATING BIOLOGICAL DISKS

Criteria	Units	Range/value
Organic loading	lb BOD_5 1,000 ft^3 of media	Without nitrification: 30-60 With nitrification: 15-20
Hydraulic loading	gpd/ft^2 of media	Without nitrification: 0.75-1.5 With nitrification: 0.3-0.6
Stages/train	-	At least 4
Parallel trains	-	At lease 2
Rotational velocity	ft/min (peripheral)	60
Media surface area	ft^2/ft^3	Disc type: 20-25
		Lattic type: 30-35
Media submerged	percent	40
Tank volume	gal/ft^2 of disc area	0.12
Detention time	min (based on 0.12 gal/ft^2)	Without nitrification: 40-9- With nitrification: 90-230
Secondary		
Clarifier overflow	gpd/ft^2	500-700
Power	hourse-power/25 ft shaft	7.5

Source: EPA, 1980

Detention Time

Typical detention times for RBDs used in municipal or industrial systems are 40-90 minutes without nitrification and 90-230 minutes with nitrification (EPA, 1980). These ranges may be applicable for leachates containing easily degradable compounds.

No simple equations are available from which a design detention time may be calculated. (The equations given previously for activated sludge and aerated impoundments might be used if the parameters x, and k can be determined.) The detention time will be a function of several variables including: (a) the nature of the wastes, influent concentrations, and desired removal efficiencies; (b) the rate of biodegradation (a function of temperature); (c) the number of discs used (expressed as disc surface area/tank volume); (d) the rotational velocity of the discs (which affects reaeration rates and the stripping of solids from the discs).

Rotational Velocity of Media

As indicated in Table 4-9, the rotational (peripheral) velocity may typically be set at about 18 m/min (60 ft/min). A higher rotational velocity may enhance biodegradation if oxygen supply is rate limiting. Lower velocities may allow the build-up of more floc on the discs and require less power. Since the rotational velocity can be changed (after installation of the RBD units), it is only important that the design provide an approximate value.

Sludge Generation Rate

It is necessary to estimate a sludge generation rate in order to properly design the post-treatment clarifier. An equation for estimating excess sludge production is provided in the discussion on Activated Sludge.

In municipal systems, sludge is generated at a rate of about 3000-4000 l per 10^6 l of wastewater(60-84 kg of dry solids per 10^6 l).

4.2.3.5 Principal Data Requirements

Generally similar to surface impoundment requirements.

4.2.3.6 Elements of Cost Review

Components

Construction and Capital--

- construction
- tanks
- biological disc
- pumps

O & M--

- electricity
- chemicals

Major Factors

Process size

Data

Construction and O & M costs as a function wastewater treated are shown in Figures 4-4 and 4-5.

4.2.4 Trickling Filters

4.2.4.1 Description

Trickling filters are a form of biological treatment in which a liquid waste of less than 1 percent suspended solids is trickled over a bed of rocks or synthetic media upon which a slime of microbial organisms is grown. The microbes decompose organic matter aerobically; these conditions are maintained at the outer slime surface by updrafts of air. Some anaerobic decomposition may occur at the interior surface adjacent to the trickling bed media. Periodically, the slime layer sloughs off due to the weight of the microbial growth or the hydraulic flow rate of the effluent. A schematic diagram of a typical trickling filter treatment system appears in Figure 4-6.

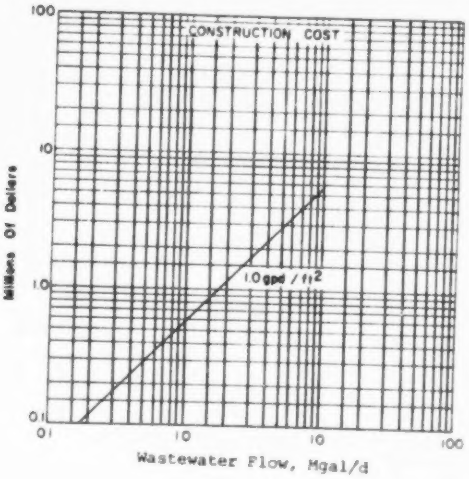
4.2.4.2 Status

Conventional; undemonstrated.

4.2.4.3 Feasibility and Effectiveness

FIGURE 4-4

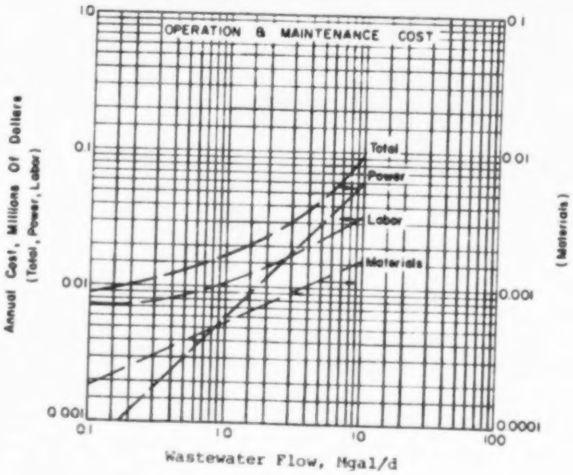
CONSTRUCTION COSTS FOR ROTATING
BIOLOGICAL DISCS[a]
(Source: EPA, 1982)



[a] to adjust costs to 1982 dollars, multiply by 1.62.

FIGURE 4-5

O&M COSTS FOR ROTATING
BIOLOGICAL DISCS[a]
(Source: EPA, 1982)



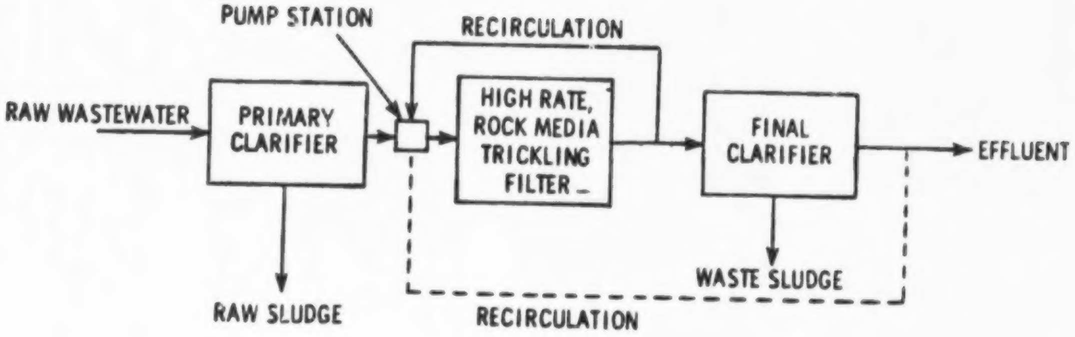
[a] to adjust to 1982 dollars, multiply by:
labor – 1.64
power – 2.0
materials – 1.52.

Basis

1. Construction cost includes RBD shafts (standard media, 100,000 ft^2/shaft), motor drives (5 hp/shaft), molded fiberglass covers, and reinforced concrete basins.
2. Cost does not include final clarifiers.
3. Loading rate - 1.0 gal/d/ft^2.

FIGURE 4-6

TRICKLING FILTER TREATMENT SYSTEM SCHEMATIC
(Source: EPA, 1980)


PUMP STATION
RECIRCULATION
RAW WASTEWATER
PRIMARY CLARIFIER
HIGH RATE, ROCK MEDIA TRICKLING FILTER
FINAL CLARIFIER
EFFLUENT
WASTE SLUDGE
RAW SLUDGE
RECIRCULATION

General Features

Trickling filters reduce BOD by 10-20 percent when used for primary treatment (roughing) and 50-90 percent when used for secondary waste treatment ("low rate") (EPA, 1982). Most current usage of trickling filters is considered "high rate;" for these, BOD removal efficiencies appear to range from 76-98 percent (EPA, 1980).

As shown in the figure above, recirculation of some wastewater is usually required to improve removal efficiencies and/or to even out flows and help operate self-propelled distributors. Recirculation may involve underflow from the trickling filter and/or over- or under-flow from the final clarifier.

A trickling filter should be capable of treating the same type of wastes as activated sludge or aerated impoundment processes. For situations involving a high-strength influent and/or a low effluent limitation (e.g., 30 mg/l BOD), it may be necessary to operate two trickling filters in series. For municipal and industrial wastewaters (which contain significant amounts of suspended solids in the raw waste), a primary clarifier is essential. Except for covered systems, the oxygen requirements can be met by natural aeration of the filter bed.

The wastewater distribution system for the filter beds may consist of stationary nozzle fields or rotating manifolds (driven by motor or self propelled from the hydraulic head). The system selected will depend on the diameter of the filter units, the flow volume and variability, and other factors. The design submitted should indicate why it is appropriate for the proposed system.

Special Precautions and Limitations

Trickling filters are considered fairly reliable as long as variations in the operating conditions (flow rates, composition) are minimized and the temperature of the wastewater remains above about 13 degrees C. Odors and flies may be a problem (EPA, 1980). Inadequate hydraulic flow rates may prevent the normal sloughing of the biological slime off the filter media; this can lead to clogging and surface ponding.

Some temperature protection is afforded by the use of covers over the filter beds. In this case, however, forced ventilation is required to maintain an air velocity of about 1 ft/min in the filter bed (Fair et al., 1968).

4.2.4.4 Design Basis

The primary design parameters to be set are:

- The type, number, size, and configuration of filter units to be used, including provisions for recycle and pre- and post-treatment.
- The pollutant load factor (expressed as lb BOD_5/ft^3 day or lb BOD_5/acre ft day).
- The hydraulic load (Mgal /acre day or gal/ft^2 day).
- The recirculation ratio.
- The sludge generation rate.

Secondary design parameters may be associated with the initial and final clarifiers, the possible need for nutrient addition and covers, the bed depth, media type, air requirements (for covered systems) and other factors.

Table 4-10 provides a summary of typical values or ranges for several design criteria of trickling filters that are applicable to municipal and industrial wastewaters.

Type, Number, Size and Configuration -- these will be determined by a number of factors. The general comments provided under the discussion of Surface Impoundments are applicable here and are not repeated. The size of the unit(s) is derived from considerations of the pollutant and hydraulic loads.

Pollutant loads -- pollutant loads typically used in industrial and municipal trickling filters are shown in Table 4-10. For high rate filters (rock or plastic media) the loads for secondary treatment are in the range of 10-60 lbs $BOD_5/1000\ ft^3$ day. The BOD load may be calculated from the raw BOD in the primary effluent, without regard to any BOD contribution in the recirculation flow (Hammer, 1975):

TABLE 4-10
DESIGN CRITERIA FOR TRICKLING FILTERS

Criteria/Factor	Unit	Value/Range
High Rate/Rock Media		
Hydraulic loading (with recirculation)	Mgal/acre/d/or gal/d/ft^2	10 - 40 230 - 900
Organic loading	lb BOD_5/d/acre ft or lb BOD_5/d/1,000 ft^3	900 - 2,600 20 - 60
Recirculation ration	-	0.5 - 4
Bed depth	ft	3 - 6
Under drain minimum slope	-	1
Power requirements	hp/Mgal	10 - 50
Dosing interval	sec	≤ 15 (continuous)
Sloughing	-	Continuous
Media - rock	in.	1 - 5
Low Rate/Rock Media		
Hydraulic loading	Mgal/acre/d or gal/d/ft^2	1 - 4 25 - 90
Organic loading	lb BOD_5/d/acre ft or lb BOD_5/d/1,000 ft^3	200 - 900 5-20
Recirculation ratio	-	0
Bed depth	ft	5-10
Under drain minimum slope	-	1
Effluent channel minimum velocity (at average daily flow)	ft/sec	2
Media - rock	in.	1-5
Sloughing		Intermittent
Dosing interval		Continuous for majority of daily operating schedule, but become intermittent during low flow periods

(Cont.)

TABLE 4-10
DESIGN CRITERIA FOR TRICKLING FILTERS (Cont.)

Plastic Media		
Hydraulic loading (with recirculation)		
a) Secondary treatment	Mgal/acre/d or gal/d/ft^2	30 - 60 700 - 1,400
b) Roughing	Mgal/acre/d or gal/d/ft^2	100 - 200 2,300 - 4,600
Organic loading		
a) Secondary treatment	lb BOD_5/d/acre ft or lb BOD_5/d/1,000 ft^3	450 - 2,200 10 - 50
b) Roughing	lb BOD_5/d/acre ft or lb BOD_5/d/1,000 ft^3	4,500 - 22,000 100 - 500
Recirculation ratio	-	0.5 - 5
Dosing interval (continuous)	sec	≤15
Sloughing	-	Continuous
Bed depth	ft	20 - 30
Power requirement	hp/Mgal	10 - 50
Under drain minimum slope	-	1

Source: EPA, 1980

$$\text{BOD load (lb/1000 ft}^3\cdot\text{day)} = \frac{Q(8.34)\text{BOD of primary effluent}}{10^{-3}\cdot\text{Volume of Filter media (ft}^3)}$$

where Q is the raw wastewater flow (Mgal/d).

Hydraulic load -- hydraulic loads for high rate filters (with recirculation, plastic or rock media) range from 230-1400 gal/ft^2 day (Table 4-10). Given a raw waste flow of Q (Mgal/d), a recirculation flow of Q_r (Mgal/d), and a filter surface area of A (ft^2), the hydraulic load is (Hammer, 1975):

$$\text{Hydraulic load (Mgal/ft}^2\cdot\text{d)} = \frac{Q + Q_R}{A}$$

Recirculation Ratio -- the recirculation ratio (R) is defined as:

$$R = \frac{\text{Recirculation flow rate}}{\text{Raw waste flow rate}}$$

For high rate filters, R is in the range of 0.5-5 (see Table 4-10). The degree of recirculation required may depend on several factors including the need to provide more even flow rates, to increase flows to enhance floc removal, to increase removal efficiencies, and/or to provide sufficient flow to operate self-propelled diffusers.

Size -- Figure 4-7 provides guidance on the optimum dimensions (for larger systems) given information on the influent and (desired) effluent BOD levels, the raw waste flow, and the recirculation ratio.

Sludge generation rate -- it is necessary to estimate a sludge generation rate in order to properly design the post-treatment clarifier. An equation for estimating excess sludge production is provided in the section on Activated Sludge. According to the EPA Treatability Manual (EPA, 1980) the following sludge generation rates are typical for municipal wastewaters:

	Sludge Generation	
	gal/Mgal	lbs dry solids/Mgal
High rate/rock media	2500 - 3000	400 - 500
High rate/plastic media	3000 - 4000	500 - 700

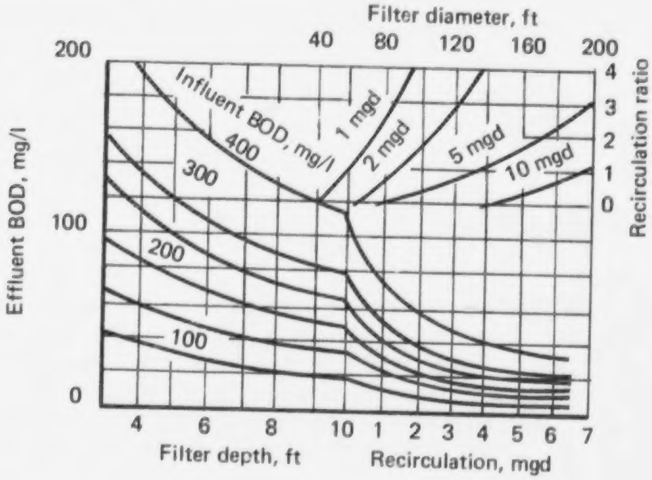
4.2.4.5 Principal Data Requirements

Generally similar to surface impoundment requirements.

4.2.4.6 Elements of Cost Review

FIGURE 4-7

OPTIMAL DIMENSIONS OF TRICKLING FILTERS
(Operated at 18°C (64°F) and Maximum Recirculation Ratios.
Hydraulic Load 30 MGAD, Maximum Depth 10 Ft.)
(Source: Fair, et al., 1968)
Used by permission, see Copyright Notice



Components

Construction and Capital--

- tanks
- pumps
- clarifier

O & M--

- chemicals
- electricity

Major Factors

Process capacity

Data

A cost example (unit and total costs) is presented in Table 4-11.

4.2.5 Land Treatment

4.2.5.1 Description

Land treatment is "the intimate mixing or dispersion of wastes into the upper zone of the soil-plant system with the objective of microbial stabilization, adsorption and immobilization leading to an environmentally acceptable assimilation of waste." (Overcash and Pal, 1979.) Land treatment differs from other land-based approaches to waste management in that the ratio of waste to soil is very low over the impacted area.

4.2.5.2 Status

- Irrigation: Conventional, undemonstrated; most widely used type of land application for treatment of municipal wastewaters. Industrial waters (i.e., paper and pulp, dairy) have also been treated in this manner. Not known if process has been applied to leachates.
- Overland flow: Developmental; overland flow has been developed for use in the U.S. for food processing wastewater effluent. Not known if the system has been applied to leachate treatment.
- Infiltration-Percolation: Conventional, undemonstrated. Has been used for pretreated municipal wastewater. Information not available for leachate.
- Leachate recycle: Developmental; relatively recent development and is not widely practiced.

TABLE 4-11
COST ESTIMATES FOR TRICKLING FILTERS

Basis: 1 x 10^6 GPD, 10,000 ppm COD, 4,000 ppm BOD, 365 day/yr operation

Estimated Capital Investment: 3,726,000

	Annual Quantity	Cost Per Unit Quantity, 1982 $	Annual Cost, 1982 $
Variable Costs			
Operating Labor	8,760 MH	19.60/hour	171,700
Maintenance (2% of Inv.)			74,500
Quicklime	400 tons	31.00/ton	12,000
Electricity	1.1 x 10^6 kWh	.04/kWh	44,000
Ammonia	330 tons	210.00/ton	69,000
Phosphoric Acid	180 tons	520.00/ton	94,000
Total Variable Costs			465,200
Fixed Costs			
Taxes and Insurance (2% of Inv.)			74,500
Capital Recovery (10% - 10 years)			601,000
Total Fixed Costs			675,500
Total Costs			1,140,700
Unit Cost ($/1000 Gal)			3.13

Source: ADL, 1976

4.2.5.3 Feasibility and Effectiveness

General Features

There are four major land treatment configurations:

- Irrigation (Figure 4-8): Leachate is sprayed (spray irrigation), flooded (flood irrigation), or applied by gravity flow (ridge and furrow irrigation) to sustain the growth of plants.
- Overland flow (Figure 4-8): Also known as "grass filtration," leachate is sprayed onto a gently-sloping, relatively impervious soil planted with vegetation. Biological treatment occurs as the wastewater contacts biota in the ground cover vegetation.
- Infiltration-Percolation (Figure 4-8): Large volumes of leachate are applied to the land, infiltrate the surface and percolate through the soil pores.
- Leachate recycle (Figure 4-9): Leachate is pumped out of the contaminated area and recycled through the plot.

Most leachates containing biodegradable pollutants can be at least partially treated by land application. Non-degradable, adsorbable species, including some heavy metals, will be retained in the soil. The degree to which specific waste cations will be adsorbed depends on the soil, waste loading, and competing cations. Most anions will not be retained in the soils.

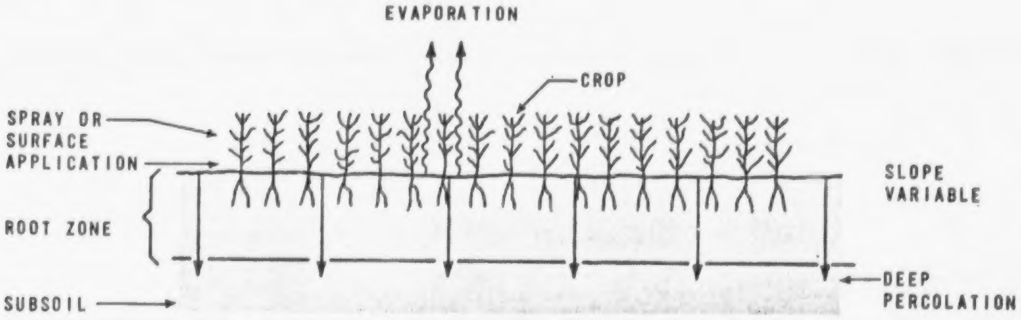
Typical removal efficiencies for conventional pollutants are shown in Table 4-12.

Biological seeding may be used to augment the activity of the indigenous soil bacteria or to offset loss of activity following a serious upset.

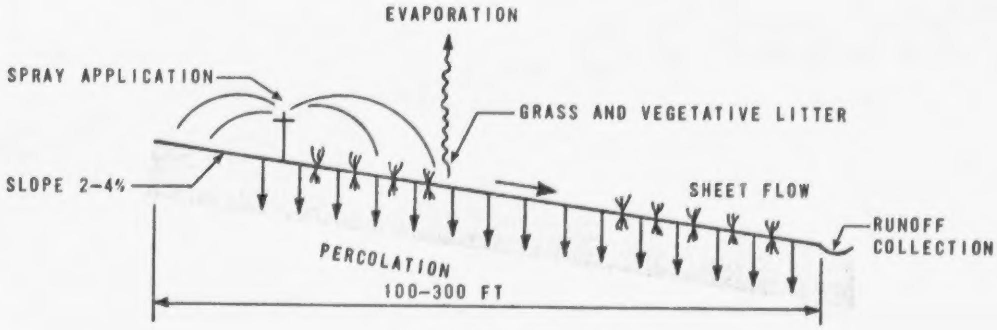
Performing rigorous calculations on assimilative capacity will minimize (but not eliminate) concerns with regard to the long-term adverse effects on the soil-plant-groundwater system. Additionally, some form of post-treatment closure care may be required.

FIGURE 4-8

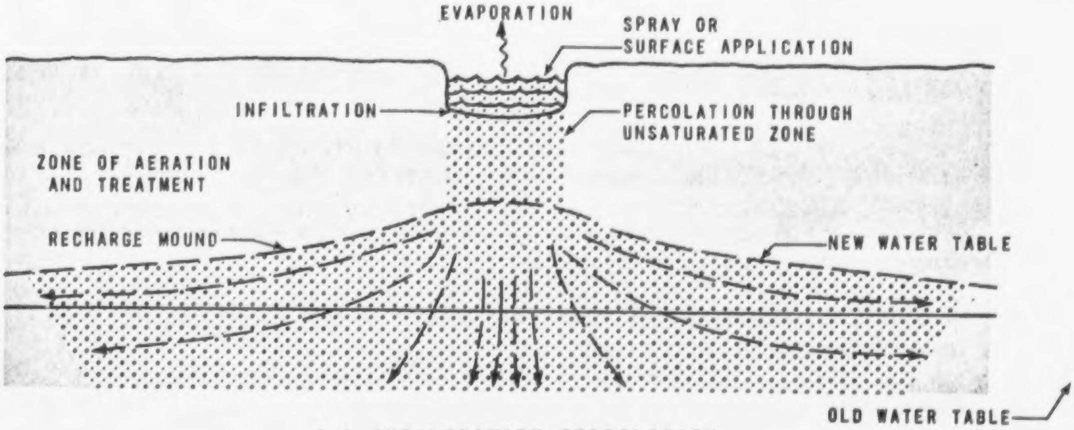
LAND APPLICATION APPROACHES
(Source: Pound and Crites, 1973)


EVAPORATION
CROP
SPRAY OR SURFACE APPLICATION
SLOPE VARIABLE
ROOT ZONE
SUBSOIL
DEEP PERCOLATION

(a) IRRIGATION


EVAPORATION
SPRAY APPLICATION
GRASS AND VEGETATIVE LITTER
SLOPE 2-4%
SHEET FLOW
RUNOFF COLLECTION
PERCOLATION
100-300 FT

(b) OVERLAND FLOW

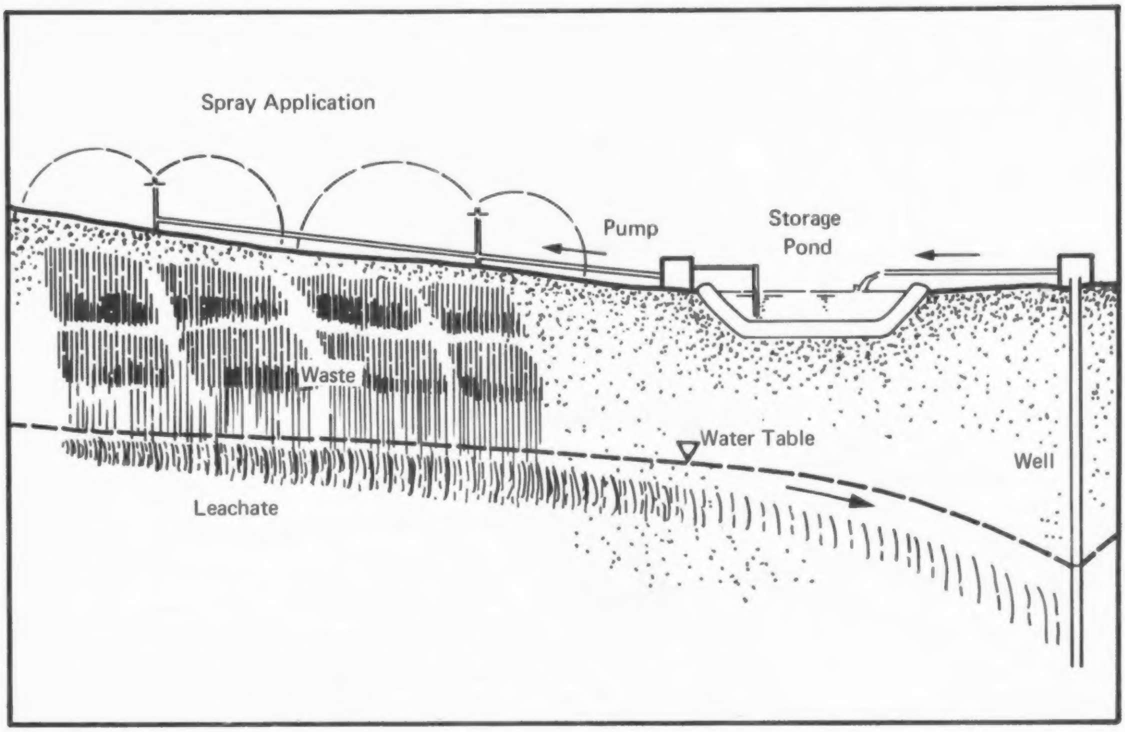

EVAPORATION
SPRAY OR SURFACE APPLICATION
INFILTRATION
PERCOLATION THROUGH UNSATURATED ZONE
ZONE OF AERATION AND TREATMENT
RECHARGE MOUND
NEW WATER TABLE
OLD WATER TABLE

(c) INFILTRATION-PERCOLATION

FIGURE 4-9

SCHEMATIC OF A LEACHATE RECYCLE SYSTEM

(Source: ADL, 1976)


Spray Application
Pump
Storage Pond
Waste
Water Table
Well
Leachate

Other concerns are:

- Salt build-up in the topsoil due to excessive water evaporation.
- Aerosol drift (fine sprays reduce the runoff potential but increase drift and associated downwind air pollution).
- Odors (volatile chemicals in leachate may easily volatilize during spray application).
- Uneven distribution of leachate over land area and/or uneven percolation rates.
- Erosion.

TABLE 4-12
REMOVAL EFFICIENCY FOR LAND TREATMENT OPTIONS

Parameter	Leachate Recycle[a]	Irrigation[b]	Overland Flow[b]	Infiltration-Percolation[a]
COD	97			
BOD	98	90-99	90-99	90-99
SS		90-99	90-99	90-99
N		<90	70-90	0-80
P		80-99	50-60	70-95

[a] anaerobic treatment after 15 days dentention time, Pohland, 1975.
[b] Pound and Crites, 1973

- Clogging of pipes and nozzles. It may be necessary to screen or filter solids from the wastes.
- Selection of crop cover, frequency of harvesting, and use of harvested crop (if any).
- Build up of other undesirable contaminants, if present.

4.2.5.4 Design Basis

In spite of its apparent simplicity, there are several components to a land treatment system for leachate. In addition to leachate collection, typical components are (Overcash and Pal, 1979):

- Transmission or conveyance
- Storage
- Application system (design, spacing)
- Land purchase and preparation for vegetative cover
- Buffer zone
- Monitoring

- Operational control systems
- Diversions and land management practices
- Agricultural equipment for vegetative cover
- Operation and management manual

While it is important for a design to be complete in its coverage of all such items, the primary design constraint is the assimilative capacity of the soil-plant-groundwater system being used. The constraint is expressed by Overcash and Pal (1979) as follows:

> The waste, when considered on a constituent by constituent basis, shall be applied to the plant-soil system at such rates or over such limited time spans that no land is irreversibly removed from some other societal usage.

They further recommend that assimilative capacity be determined for three broad types of pollutants:

- Those that degrade or require plant uptake for assimilation in the plant-soil system, e.g., oils or organics;
- Those that are relatively immobile and nondegradative, thus are permitted to accumulate in soils to predetermined critical levels, e.g., heavy metals; and
- Those that are mobile and nondegradable and must be assimilated over land areas so that receiving waters are not altered to a degree requiring further drinking water treatment, e.g., anionic species.

The calculation of assimilative capacity for each pollutant of concern must consider not only the nature of that pollutant (biodegradability, mobility, uptake, toxicity); but also the site environmental factors (soil type, meteorology, hydrogeology). Maximum site life is dependent on the accumulation rate and acceptable soil levels of immobile, nondegradable contaminants such as heavy metals. A significant amount of laboratory and/or field data may be required. (Additional details on such calcualtions are provided by Overcash and Pal, 1979.)

In each case the assimilative capacity calculated (e.g., in kg/ha/yr) and compared with the waste generation rate (kg/yr) derived from data on leachate composition and collection rates. The ratio of these two numbers is the land area (ha) required to assimilate each constitutent. The constituent with the largest land area requirement is referred to as the land-limiting constituent (LLC). If all of the pollutants are easily assimilated, it is possible that water could be the LLC as a result of the soil permeability and other factors.

The assimilative capacity for the land-limiting constituents(s) should be estimated for different seasons. This can then be translated into a leachate assimilative capacity expressed in terms of leachate depth applied per unit time (e.g., cm/mo). The following equations can be used:

$$\text{Leachate Assimilative Capacity (cm/mo)} = \frac{F}{A \cdot 100} \qquad (1)$$

$$= \frac{F \cdot C}{R \cdot 100} \qquad (2)$$

$$= \frac{C}{X \cdot 1200} \qquad (3)$$

where:

F = Leachate flow rate (m^3/mo)

A = Area of land application (ha) = R/C

C = Assimilative capacity of system for LLC (kg/ha·yr)

R = Rate of waste generation/application (kg/yr) = $12 \cdot F \cdot X$

X = Concentration of LLC in leachate (kg/m^3)

Leachate storage requirements can be estimated by comparing such monthly assimilative capacities with leachate volumes being generated. Note that storage requirements can be minimized by using a land application area derived from a worst-case application of equations 1, 2, or 3. In many cases, this will be the winter months when biological activity and permeabilities are reduced. The maximum storage requirement in northern climates may be as much as 160 days; in the northwest and southeast portions of the U.S., storage may be required during prolonged wet spells (Overcash and Pal, 1979). Table 4-13 lists ranges of typical design parameters for these land treatment techniques used for municipal wastes. These design parameter values may differ significantly from those needed to accommodate land treatment of leachate.

TABLE 4-13
COMPARATIVE CHARACTERISTICS OF LAND APPLICATION APPROACHES

Feature	Slow rate	Rapid Infiltration	Overland flow
Application techniques	Sprinkler or surface[a]	Usually surface	Sprinkler or surface
Annual loading rate, m	0.5-6	6-125	3-20
Field area required, ha[b]	23-280	3-23	6.5-44
Typical weekly loading rate, cm	1.3-10	10-240	6-40[c]
Disposition of applied wastewater	Evapotranspiration and percolation	Mainly percolation	Surface runoff and evapotranspiration with some percolation
Need for negotiation	Required	Optional	Required
Grade	Less than 20% on cultivated land; less than 40% on noncultivated land	Not critical; excessive grades require much earthwork	Finish slopes 2-8%[d]
Soil permeability	Moderately slow to moderately rapid	Rapid (sands, sandy loams)	Slow (clays, silts, and soils with impermeable barriers)
Depth to ground water	0.6-1 m (minimum)[e]	1 m during flood cycle[e]; 1.5-3 m during drying cycle	Not critical[f]
Climatic restrictions	Storage often needed for cold weather and during heavy precipitation	None (possibly modify operation in cold weather)	Storage usually needed for cold weather

a. Includes ridge-and-furrow and border strip.

b. Field area in hectares not including buffer area, roads, or ditches.

c. Range includes raw wastewater to secondary effluent, higher rates for higher level of preapplication treatment.

d. Steeper grades might be feasible at reduced hydraulic loadings.

e. Underdrains can be used to maintain this level at sites with high ground water table.

f. Impact on ground water should be considered for more permeable soils.

Source: EPA, 1981

Additional information on design of land treatment facilities can be found in TRD 8.

4.2.5.5 Principal Data Requirements

Assimilative capacity of the soil-plant-groundwater system. (Details for specific pollutants may require data on biodegradability, uptake, mobility and toxicity can be found in Table 4-14.) Calculations should identify the land-limiting contaminant (LLC) and the acceptable seasonal assimilative capacity rates.

Leachate composition and flow (including variability in time)

Characteristics of the soil in area to be used (type, organic carbon content, cation exchange capacity, permeability, etc.)

Meteorology (temperatures, precipitation, solar insolation)

Local hydrogeology (groundwater depth and flows, runoff potential, water uses)

Various aspects of the last three items are presented in Table 4-15 which lists site selection factors and criteria for municipal waste waters. Selection criteria for land treatment of leachate from hazardous waste sites may differ.

4.2.5.6 Elements of Cost Review

Components

Construction and Capital--

- application equipment
- monitoring instrumentation

O & M--

TABLE 4-14
ESSENTIAL CONSIDERATIONS IN A COMPREHENSIVE TESTING PROGRAM FOR APPRAISING WASTE-SITE INTERACTIONS

Waste Site Interactions	Test Method	Manual Reference
Degradation of waste	Respirometry	7.2.1
	Field studies by soil testing	7.5.3.1.4
Accumulation in soil of nondegradables	Waste analysis (inorganics)	6.4
	Respirometry (organics)	7.2.1
Leaching hazards	Soil thin layer chromatography	7.2.2.1
	Soil leaching columns	7.2.2.2
	Field soil leachate testing	7.5.3.1.2
Run-off hazards	Rainfall simulation	7.2.2.3
Volatilization hazards	Environmental chamber	7.2.3
	Field air testing	7.5.3.1.1
Acute toxicity	Respirometry (soil biota)	7.2.1
	Greenhouse pot studies (plants)	7.3
Chronic toxicity	Microbiological mutagenicity assays	7.2.4
Plant uptake (optional)	Greenhouse pot studies	7.3
Pretreatment	Assessment of processes generating waste	6.3

Source: TRD 8

TABLE 4-15
SITE SELECTION FACTORS AND CRITERIA FOR EFFLUENT IRRIGATION[a]

Factor	Criterion
Soil	Loamy soils preferable but most soils from sands to clays are acceptable.
Soil drainability	Well drained soil is preferable; consult experienced agricultural advisors.
Soil depth	Uniformly 5 to 6 ft or more throughout sites is preferred.
Depth to groundwater	Minimum of 5 ft is preferred. Drainage to obtain this minimum may be required.
Groundwater control	May be necessary to ensure renovation if water table is less than 10 ft from surface.
Groundwater movement	Velociity and direction must be determined.
Slopes	Up to 15 percent are acceptable with or without terracing.
Underground formations	Should be mapped and anlyzed with respect to interference with groundwater or percolating water movement.
Isolation	Moderate isolation from public preferable, degree dependent on wastewater characteristics, method of application, and crop.
Distance from source of wastewater	A matter of economics

[a] Based on municipal wastewater.
Source: Pound and Crites, 1973

- pH control

Major Factors

- Site preparation requirements

Data

Costs are very sensitive to site and waste specific factors. For detailed cost information and cost estimating techniques for land treatment systems, see Reed, 1979.

4.3 CHEMICAL TREATMENT

4.3.1 Neutralization

4.3.1.1 Description

Neutralization, used by itself, is a process used to adjust the pH (acidity or alkalinity) of a waste stream to an acceptable level for discharge, usually between 6.0 to 9.0 pH units. Neutralization may also be used as a pre- or post-treatment step with other treatment processes. Adjustment of pH is done by adding acidic reagents or acidic wastes to alkaline streams and vice versa. Figure 4-10 shows a three-stage neutralization system schematic including:

- initial neutralization
- equalization
- final adjustment

There are other alternative configurations.

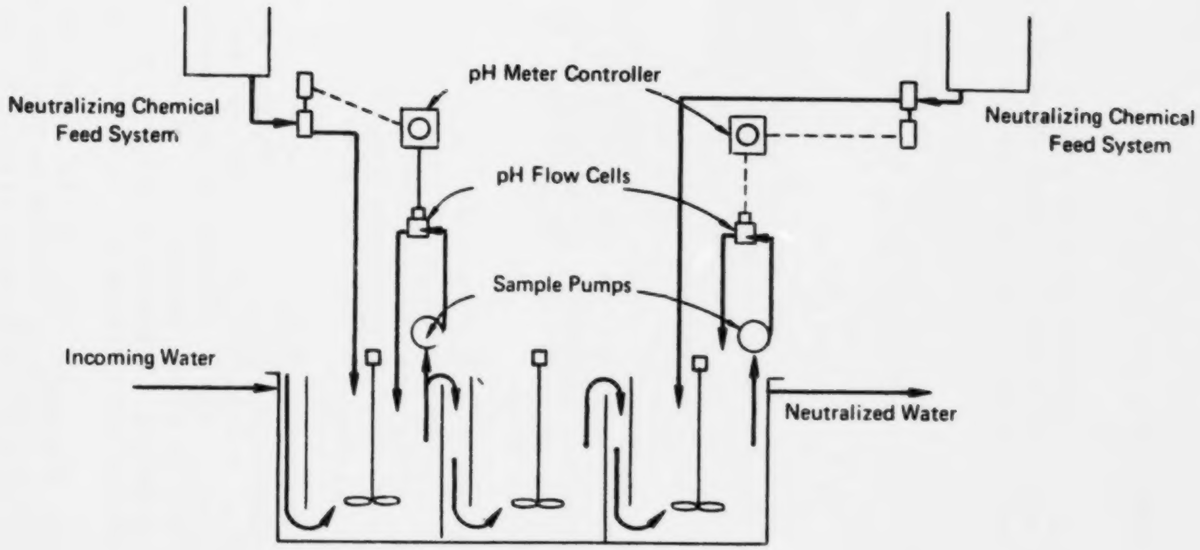
4.3.1.2 Status

Conventional, demonstrated.

FIGURE 4-10

NEUTRALIZATION TREATMENT SYSTEM SCHEMATIC DIAGRAM

(Source: ADL, 1976)


Neutralizing Chemical Feed System
pH Meter Controller
Neutralizing Chemical Feed System
pH Flow Cells
Sample Pumps
Incoming Water
Neutralized Water

4.3.1.3 Feasibility and Effectiveness

General Features

Neutralization is generally applicable to aqueous leachate streams; some non-aqueous materials such as acid phenols and carboxyl acids can also be treated by neutralization.

The selection of reagent depends strongly on cost considerations. The salient characteristics of the most common reagents are:

- Sulfuric Acid -- Commonly preferred acid reagent because of its relatively lower cost. It does have the potential to form insoluble salts which present equipment scaling and solids handling problems.
- Hydrochloric Acid -- Neutralization products are generally soluble which eliminates the problems associated with solids formation. However, it is important to consider discharge limitations on dissolved solids when using hydrochloric acid.
- Sodium Reagents (caustic soda, soda ash) -- Because sodium reagents are very soluble in water relative to other basic reagents, they can be handled as concentrated solutions which reduce storage and equipment capacity requirements. Raw material costs are higher than other basic reagents.
- Calcium Reagents (lime, quicklime, limestone) -- Calcium reagents have low water solubilities and are generally fed to a neutralization tank as slurries on the order of 15 percent solids. This increases the capital cost asociated with handling these reagents. If sulfate ions are present in the leachate, insoluble calcium sulfate will be formed posing potential scaling and solids handling problems.
- Magnesium Reagents (dolomitic lime, dolomitic limestone) -- Magnesium reagents eliminate the scaling and solids formation problems associated with calcium reagents and wash-streams containing sulfate ions.

Waste acids or alkalies, if available, can be used to neutralize leachate streams.

Special Precautions and Limitations

The reagents used in neutralization and the untreated waste may be quite corrosive. It is important to select compatible construction materials. Appropriate materials (at ambient temperatures) for each of the principal reagent classes are:

- Sulfuric acid (75-95%) -- lead: (<10%) -- lead or rubber;
- Hydrochloric acid (dilute or concentrated) -- rubber;
- Sodium base (concentrated) -- 316SS or rubber, (dilute) -- 316SS, rubber, carbon steel, or cast iron;
- Calcium base -- 316SS, rubber, or carbon steel.

4.3.1.4 Design Basis

Principal design parameters are:

- flow
- neutralization reagent addition rate

Reagent addition rate is determined by laboratory tests to prepare a neutralization curve, showing the amount of reagent added to a unit quantity of wastes versus resultant pH. Figure 4-11 shows a typical curve.

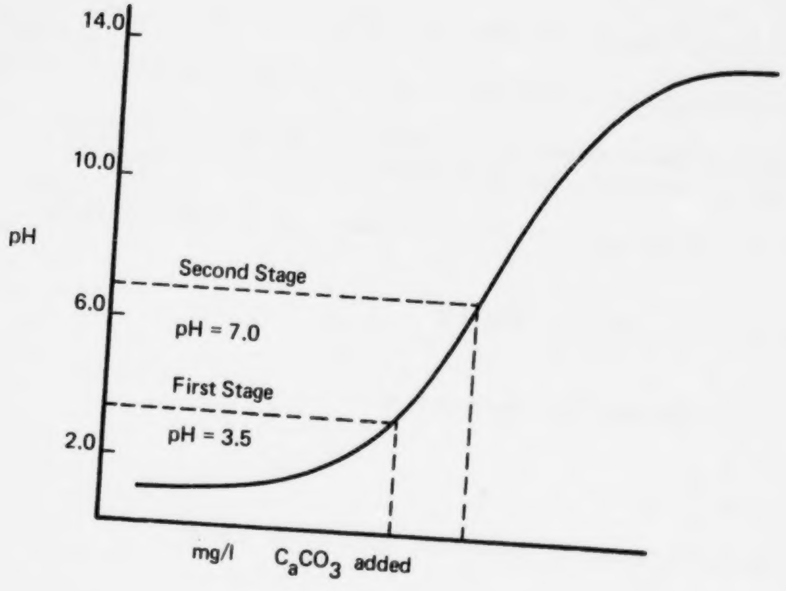
Tank sizes are based on the flow and detention time which is typically 5 to 10 minutes per stage (Adams and Eckenfelder, 1974). The tank size capacity is calculated as follows:

$$\text{T.S.} = \frac{\text{flow}}{\text{R.T.}} (\#\text{Stages})$$

FIGURE 4-11

NEUTRALIZATION CURVE

(After: Adams & Eckenfelder, 1974)



where:

T.S. = tank size
flow = flow of influent
R.T. = reaction time
#Stages = number of neutralization stages

Mixing power levels are (Adams and Eckenfelder, 1974):

- for air systems -- 1 to 3 scfm/ ft^2 for a 9-foot liquid depth; and
- for mechanical system -- .2 to .4 hp/1000 gal

4.3.1.5 Principal Data Requirements

- expected leachate average daily and variability of flow rate (system size)
- leachate acidity or alkalinity (mg/l $CaCO_3$) (reagent requirements)
- pH titration curve, as shown in Figure 4-11 (reagent requirements)

4.3.1.6 Elements of Cost Review

Components

Construction and Capital--

- tanks
- pumps
- mixers
- monitoring instrumentation

O & M--

- chemicals
- electricity

Major Factors

- process volume
- neutralization chemical requirements

Data (Adams and Eckenfelder, 1974)

Capital and O & M costs in 1982 dollars, are $936,000 - $1,170,500 and 1,000 per million gallons treated, respectively, for a neutralization system to treat:

- 500,000 gpd
- 20,000 mg/l $CaCO_3$ equivalent
- 100 - 500 mg/l suspended solids

4.3.2 Precipitation

4.3.2.1 Description

Precipitation is a widely used (in industrial practice), relatively low-cost physical chemical technique in which the chemical equilibrium of a waste is changed to reduce the solubility of the undesired components. These components precipitate out of solution, as a solid phase, often in the form of small or even colloidal particles, and are removed by one of several possible solids removal techniques. Precipitation is most commonly used to treat heavy metals-containing wastes.

4.3.2.2 Status

Conventional, demonstrated.

4.3.2.3 Feasibility and Effectiveness

General Features

Precipitation is induced by one of the following means:

- adding a chemical that will react with the hazardous constituent in solution to form a sparingly soluble compound.
- adding a chemical to cause a shift in solubility equilibrium, reducing the solubility of the hazardous substance.
- changing the temperature of a saturated or nearly saturated solution in the direction of decreased solubility.

Chemical additives are most commonly used. Typical reagents are:

- sodium hydroxide, sodium sulfide
- lime ($Ca(OH)_2$)
- iron salts, iron sulfide, ferric sulfate
- phosphate salts (especially for heavy metals such as As, Cd, Cr, Zn, Cu, Pb, Hg, Ni)
- alum ($Al_2(SO_4)_3$)

The theoretical removal limits for many metal species is very low, particularly with sulfide precipitants. Figure 4-12 shows theoretical curves as a function of waste pH. Some organic species -- for example, aromatic compounds and phthalates -- can also be treated. Removal in practice often is one to two orders of magnitude less than the theoretical limit. Complexing agents, such as cyanide or EDTA, compete with the precipitant and may hold the species in solution.

Conventional precipitation processes are performed in the following three steps:

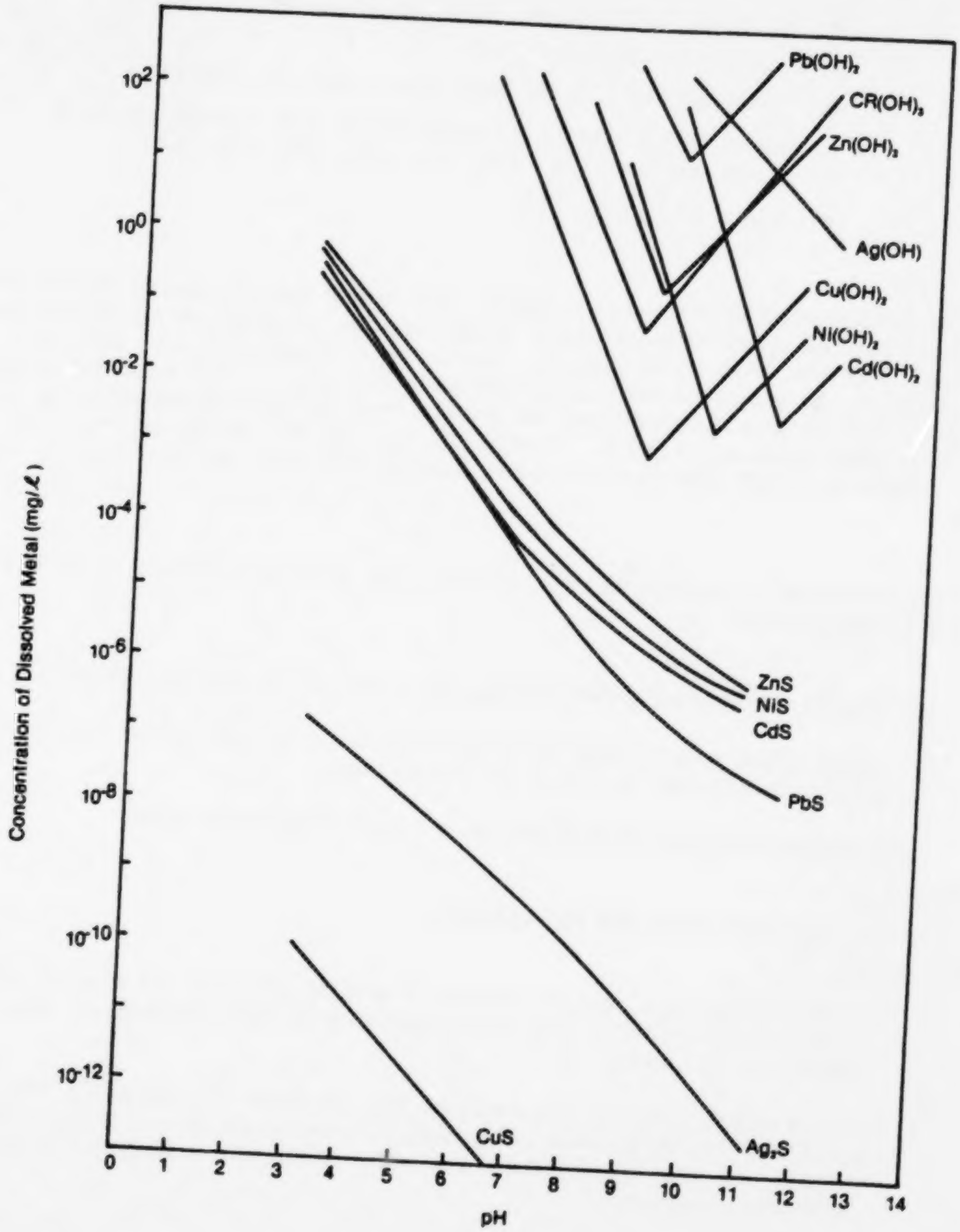
1. rapid mixing of precipitating chemicals and wastewater;
2. slow mixing of treated wastewater in a flocculation tank to allow settleable flocs to form; and
3. sedimentation of solids in a clarification tank.

The solids are removed by either:

- sedimentation, which separates the phases by the gravitational settling of the precipitate to the bottom of the sedimentation tank;
- filtration, which separates the phases by passing the precipitation effluent through a granular or cloth barrier, retaining the particles and allowing the clear effluent to pass through, or

FIGURE 4-12
SOLUBILITY OF METAL HYDROXIDES AND SULFIDES

(Source: Ghassemi, et al., 1981)



- centrifugation, which separates the two phases in an enclosed vessel using centrifugal force to cause the solids to migrate through the liquid.

Special Precautions and Limitations

As noted, removal can be limited in the presence of complexing agents in the wastes. This problem can generally be eliminated by:

- using a sulfide precipitation agent;
- breaking up the metal complex by altering pH to either a basic or acidic extreme and adding a substitute cation to tie up the complexing agent when the pH is readjusted to precipitate the metal; and
- using insoluble starch xanthate as a precipitation agent (not widely used).

The sludge produced by precipitation should be considered hazardous unless laboratory tests show otherwise.

4.3.2.4 Design Basis

The major design factors are:

- effluent criteria
- leachate flow and
- concentration of precipitable ions in the leachate.

Based on the wastewater analyses and solubility curves for the species to be removed, laboratory tests are designed to determine optimum precipitation conditions and chemical requirements to satisfy effluent criteria.

A mixing tank is sized based on the leachate flow and precipitation chemical/leachate contact time required. Generally, contact time ranges from 10 to 60 minutes. Flocculation tank sizes are based on flow and retention time (typically 30 to 60 minutes). Clarification tank size is based on laboratory experiments to determine the settling rate and the leachate flow.

4.3.2.5 Principal Data Requirements

Leachate analysis (reagent choice, size)

- precipitable constituents
- interfering species (i.e., cyanide, EDTA, etc.)

Leachate daily average and variations on flow

Treatability study (size, reagent choice, and rate)

- optimum precipitation conditions
- settling rate
- sludge production rate

- leachate flow;
- wastewater analyses of precipitable constituents;
- wastewater analyses for constituents that interfere with precipitation (i.e., cyanide, EDTA, etc.);
- optimum precipitation conditions;
- settling rate of precipitate; and
- sludge production rate.

4.3.2.6 Elements of Cost Review

Components

Construction and Capital--

- tanks
- pumps
- mixers

O & M--

- chemicals
- electricity

Major Factors

process volume

Data

Sample costs for several different capacity precipitation systems are given in Table 4-16.

4.3.3 Reduction (For Cr)

4.3.3.1 Description

Toxic hexavalent chromium ion (Cr VI) can be reduced to the less toxic trivalent chromium ion (Cr III). The reduction process is followed by Cr III removal through precipitation as the insoluble sulfate. Chrome reduction is carried out by adding a reducing agent under highly acidic conditions (of pH 2 to 3). Figure 4-13 shows a typical flow reactor treatment process layout for Cr VI reduction.

4.3.3.2 Status

Conventional, demonstrated.

TABLE 4-16
PRECIPITATION, FLOCCULATION, AND SEDIMENTATION COST ESTIMATES AS A FUNCTION OF SIZE

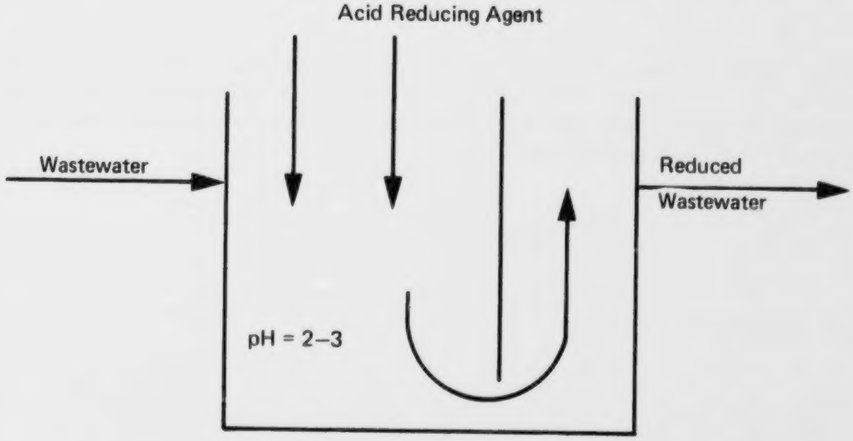
Basis: -Wastewater from Automotive Plating Operation
-Flowrate = 410,000 gpd, 350 day/year, 24 hour day
-Zinc Concentration = 113 mg/1
Capital Investment - $487,600

	Treatement System Size (Wastewater Flowrate)		
	82,000 gpd	410,000 gpd	2,050,000 gpd
Capital Investement	$171,700	$487,600	$1,388,300
Variable Cost			
Labor	72,400	109,800	165,100
Maintenance (4% Inv.)	6,900	19,500	55,500
Chemicals			
Quicklime	400	1,800	8,900
Coagulant Aid	1,400	7,300	36,300
Sulfuric Acid	220	1,100	5,500
Electrical Energy	1,300	6,000	29,800
Total Variable Cost	$ 82,500	$145,500	$ 301,100
Fixed Cost			
Capital Recovery	27,500	78,000	222,100
Taxes and Insurance (2% Inv.)	3,400	9,800	27,800
Total Fixed Cost	$ 30,900	$ 87,800	$ 249,900
Total Annual Cost	$113,400	$233,300	$ 551,000
Unit Cost ($/1000 Gal)	$ 3.95	$ 1.63	$ .77

Source: ADL, 1976

FIGURE 4-13

CHROMIUM REDUCTION TREATMENT SYSTEM


Acid Reducing Agent
Wastewater
Reduced Wastewater
pH = 2–3

4.3.3.3 Feasibility and Effectiveness

General Features

Reducing agents include:

- SO_2 (gas)
- $NaHSO_3$
- $FeSO_4$
- Waste pickling liquor

Selection is most often made on cost considerations and the availability of the reagents. Sulfuric acid is most commonly used to acidify the solution.

The effluent from this process must be filtered or clarified to remove the sulfate precipitate. Neutralization will also be required to increase the pH to acceptable levels for discharge (pH 6 to pH 9). Residual hexavalent chromium levels can be reduced to less than 1 ppm.

Special Precautions and Limitations

Cyanides may also be present along with hexavalent chromium. To avoid possible release of toxic hydrogen cyanide at the low pH (acidic) conditions necessary for reduction, cyanide removal should always precede this treatment.

4.3.3.4 Design Basis

Design parameters are:

- Reaction tank size -- The reduction reactions are rapid. A retention time of 5 to 15 minutes should be sufficient to achieve thorough mixing and reduction to hexavalent chromium. Tank size for the reduction system is calculated by:

  $V_T = R \times F$

  where:

  V_T = tank volume
  R = retention time
  F = flow

- Chemical requirements -- Estimates can be made by using wastewater analysis and the general stoichiometry for each reactant type as:

• SO_2	2.5 g/gCr
• $NaHSO_3$	3 g/gCr
• $FeSO_4$	9 g/gCr

Laboratory reduction tests are a more accurate means of determining reactant requirements.

4.3.3.5 Principal Data Requirements

Leachate daily average and variations in flow rate (Chemical requirements);

Leachate analysis (reagent requirements, size)

- hexavalent chromium concentration in leachate
- pH

4.3.3.6 Elements of Cost Review

Components

Construction and Capital--

- tanks
- pumps
- mixers
- monitoring instrumentation

O & M--

- chemicals
- electricity

Major Factors

- Process size
- Level of treatment desired

Data

A cost example (unit and total costs) for a 2,000-gallon per day reduction system is presented in Table 4-17.

4.3.4 Wet Air Oxidation

4.3.4.1 Description

Wet air oxidation (WAO) is a type of combustion, occurring in the liquid phase, through addition of air at high pressures and elevated temperature. The reactions take place in a reactor, which may contain a catalyst to promote the oxidations reactions. Figure 4-14 shows a schematic of the WAO process. The products of reaction are steam, N_2 , CO_2, and an oxidized liquid stream.

4.3.4.2 Status

Developmental

4.3.4.3 Feasibility and Effectiveness

General Features

The WAO process is attractive for liquid wastes containing insufficient heat value to support self-sustaining incineration. WAO can be self-sustaining at levels above about 15,000 ppm COD (although higher levels are more typical), while conventional liquid incineration requires levels of at least 300,000 to 400,000 ppm COD. WAO works well on waste, too concentrated for conventional biological treatment. Process conditions are typically:

- pressure - 24 atm (350 psi)
- temperature - 300 degrees C
- waste composition--5-15 percent oxidizable organics by weight.

Performance capabilities of WAO are dependent on the waste stream being treated. Destruction efficiency for ten priority pollutants is shown in Table 4-18.

TABLE 4-17
ESTIMATED OPERATING COSTS FOR REDUCTION

Basis:	- Stream Flow:	2,000 gallons per day
	- Treatment:	batch
	- Influent Concentrations	100,000 ppm CrO_3 (85% as Cr^{3+}) in 20% H_2SO_4
	- Effluent Concentrations:	undetectable - Cr^{6+}
	- Raw Material Dosage	

sulfur dioxide	- 240 pounds/day
lime	- 2,065 pounds/day

Capital Investment - $372,600

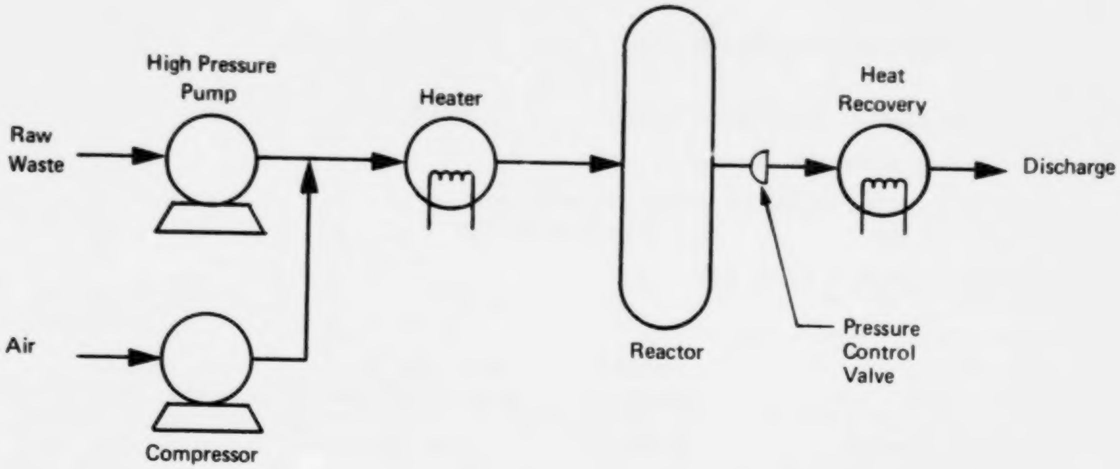
Variable Cost	Annual Quantity	Cost Per Unit Quantity, 1982 $	Annual Cost 1982 $
Operating Labor	2,500 MH	$19.60/hr	$ 49,000
Chemicals			
Sulfur Dioxide	29 tons	275/ton	8,000
Quicklime	250 tons	31.00/ton	7,800
Total Chemical Costs			$ 15,800
Utilities			
Electricity	35,000 kWh	$ .04/kWh	$ 1,400
Maintenance - (3% Inv.)			11,200
Total Variable Costs			$ 77,400
Fixed Costs			
Taxes and Insurance (2% Inv.)			$ 7,500
Capital Recovery (10 yrs @ 10%)			59,900
Total Fixed Costs			$67,400
Total Annual Cost			$144,800
Unit Cost ($/$10^3$ gal)			$301.67

Source: ADL, 1976

FIGURE 4-14

SCHEMATIC OF WET AIR OXIDATION

(After: Ghassemi, 1981)


High Pressure Pump
Heater
Heat Recovery
Raw Waste
Discharge
Air
Reactor
Pressure Control Valve
Compressor

The safety problems associated with the use of high presure WAO systems require conformance to applicable operating safety codes (e.g., ASME codes).

Special Precautions and Limitations

None noted.

4.3.4.4 Design Basis

Key design factors include (Ghassemi et al., 1981; EPA, 1982):

- reactor pressure (operating pressures range from 150 to 4000 psi, typical operating pressure is 350 psi);
- operating temperature (operating temperatures range from 200 to 320 degrees C, typical operating temperature is 300 degrees C);

TABLE 4-18
WAO EFFICIENCY FOR TEN PRIORITY POLLUTANTS

Compound	Starting concentration (g/l)	% Starting material destroyed	
		320°C	275°C
Acenaphthene	7.0	99.96	99.99
Acrolein	8.41	>99.96[a]	99.05
Acrylonitrile	8.06	99.91	99.00[b]
2-Chlorophenol	12.41	99.86	94.96[b]
2,4-Dimethylphenol	8.22	99.99	99.99
2,4-Dinitrotoluene	10.0	99.88	99.74
1,2-Diphenylhydrazine	5.0	99.98	00.08
4-Nitrophenol	10.0	99.96	99.60
Pentachlorophenol	5.0	99.88	81.96[b]
Phenol	10.0	99.97	99.77

[a] The concentration remaining was less than the detection limit of 3 mg/l.

[b] The % destruction for acrylonitrile, 2-chlorophenol, and pentachlorophenol at 275°C were increased to 99.50, 99.88, and 97.3 by addition of cupric sulfate (catalyst).

Source: Ghassemi, et al., 1981

- retention time (sample oxidation efficiencies at various temperatures as a function of retention time are illustrated in Figure 4-15);
- use of catalysts; and
- use of batch on continuous system.

4.3.4.5 Principal Data Requirements

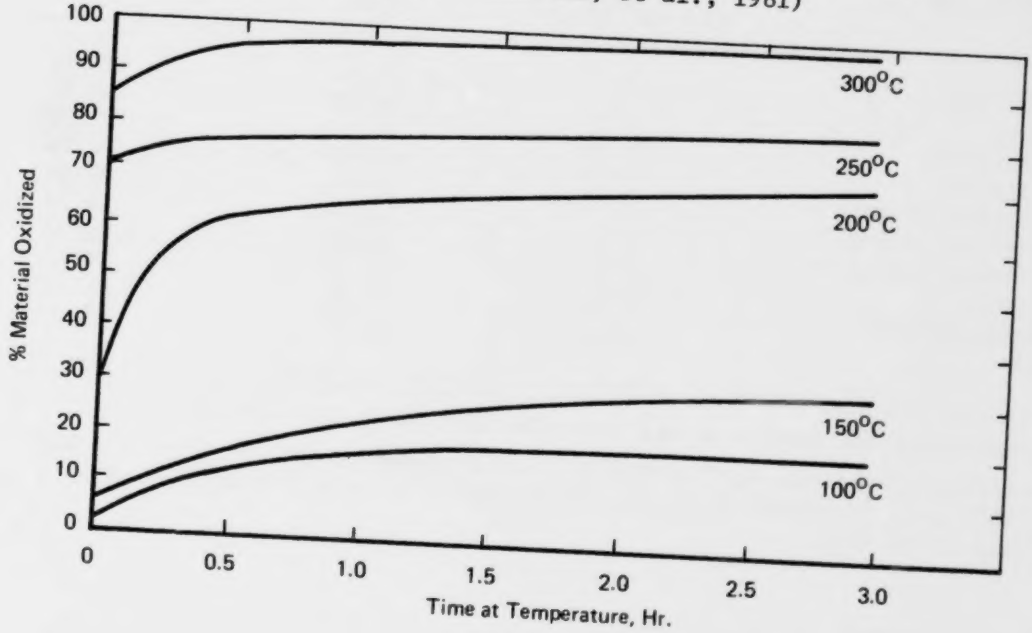
Leachate daily average and variations in flow (size)

Concentration of oxidizable materials in the wastewater (size, air requirements); and

Treatability study (laboratory-scale):

- rates of reaction
- pressure

FIGURE 4-15
TIME-TEMPERATURE EFFECT ON THE DEGREE OF OXIDATION
(Source: Ghassemi, et al., 1981)



- temperature
- air addition requirements
- retention time

4.3.4.6 Elements of Cost Review

Components

Construction and Capital--

- reactor vessel (stainless steel)
- tanks
- high pressure pump

O & M--

- electricity

Major Factors

- process size
- operating pressure

Data

Installed capital costs is 2.0 million 1982 dollars, for a unit capable of:

- processing 20 gallons per minute; and
- reducing influent COD levels of up to 80,000 mg/l by 80%.

Total annual operating costs for the wet air oxidation unit described above is $148,000, 1982 dollars (Wilhelmi and Knopp, 1979).

4.3.5 Chlorination (For Cyanide Only)

4.3.5.1 Description

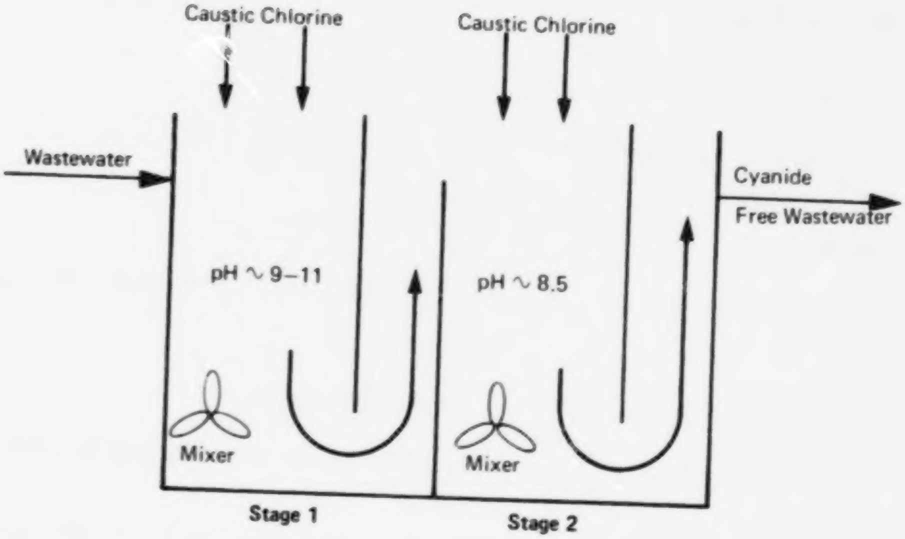
Chlorination of alkaline cyanide-containing wastes removes cyanide by oxidation in stages to the less toxic cyanate ion and then to non-toxic bicarbonates and nitrogen. Caustic and chlorine are added to the wastes in either a batch or flow reactor. Figure 4-16 shows a schematic of a two-stage flow reactor, a configuration often used to minimize size or retention time by optimizing the reaction stages through pH control.

4.3.5.2 Status

Conventional, demonstrated.

FIGURE 4-16

CYANIDE CHLORINATION TREATMENT


Caustic Chlorine
Caustic Chlorine
Wastewater
Cyanide
Free Wastewater
pH ~ 9–11
pH ~ 8.5
Mixer
Mixer
Stage 1
Stage 2

4.3.5.3 Feasibility and Effectiveness

General Features

Cyanide destruction is used not only to reduce the hazard of hydrogen cyanide gas generation under acidic conditions, but also as a pretreatment for some heavy metal treatments, such as precipitation, where cyanide complexes interfere with metal removal (White, 1972).

Chlorination is broadly applicable to cyanide containing wastes of highly varying composition. Residual cyanide concentrations can be reduced to levels below 1 ppm.

System configurations include:

- batch reactors

- continuous flow reactors (preferred at flows greater than 1200 gal/hr)

Common chlorination sources are:

- chlorine gas
- sodium hypochlorite

The reaction rates are quite sensitive to pH.

Special Precautions and Limitations

The pH must be very closely monitored to avoid development of acid conditions, under which highly toxic hydrogen cyanide gas can be generated. Good mixing is also essential to avoid acidic regions, even though the overall conditions remain basic. Systems should include pH monitors, sufficient mixing power, and carefully designed baffles for these purposes. Oxidation-reduction potential (ORP) probes should also be installed to control chlorine additions. Chlorine is acutely hazardous and should be handled accordingly.

Excess chlorine may react with other constituents in the waste to form other hazardous compounds. This problem is potentially greater in remedial action situations where waste composition may be both poorly characterized and more variable than in conventional industrial waste treatment applications.

4.3.5.4 Design Basis

The principal design considerations are:

- tank volume which is calculated on the basis of a retention time of about 30 minutes per stage for a two-stage system and flow rate is as follows:

$$V_s = F(.5/hr)$$

where:

V_s = tank volume per stage (ft^3)

F = leachate flow (ft^3/hr)

- Chemical requirements which are determined by laboratory testing.

4.3.5.5 Principal Data Requirements

Leachate daily, average and variations flow (volume)

Leachate analysis

- leachate average and variations in cyanide concentration (reagent rate)
- potential for formation of hazardous chlorinated by-products

4.3.5.6 Elements of Cost Review

Components

Construction and Capital--

- tanks
- pumps
- mixers
- monitoring instrumentation

O & M--

TABLE 4-19
ESTIMATED COSTS FOR CHEMICAL OXIDATION

Basis:
- Stream Flow: 1,000 gallons per day
- Treatment: batch / complete oxidation
- Influent Concentrations: 7,000 ppm copper cyanide
  1,000 ppm sodium cyanide
- Effluent Concentrations: 0 ppm cyanide
- Raw Material Dosage: NaOH 95 pounds/day
- Operation: Chlorine 227 pounds/day,

Capital Investment: $162,000 240 days/year

Variable Costs	Annual Quantity	Cost per Unit Quantity, 1982 $	Annual Cost, 1982 $
Operating Labor	2,000 MH	19.60/MH	39,200
Chemicals			
Sodium Hydroxide	11.5 tons	350/ton	4,000
Chlorine	29.5 tons	145/ton	4,300
Total Chemical Costs			
Utilities			
Electricity	12,000 kWh	.04/kWh	480
Cooling Water	360 M gal	0.15/1000 gal.	50
Total Utilities			530
Maintenance @ 4% of Inv.			6,500
Total Variable Costs			54,500
Fixed Costs			
Taxed Insurance @ 2% Inv.			3,200
Capital Recovery (10 yrs @ 10%)			26,400
Total Fixed Costs			29,600
Total Annual Costs			84,100
Unit Cost, $\$/10^3$ Gallons			350.42

Source: ADL, 1976

- chemicals
- electricity

Major Factors

- process size
- level of treatment desired

Data

A cost example (unit and total costs) for a 1,000 gallon per day chlorination system is presented in Table 4-19.

4.3.6 Ozonation

4.3.6.1 Description

In ozonation, contact with ozone -- a powerful oxidizing agent -- breaks down many refractory organic compounds not treatable with biological treatment techniques. Ozone, produced in a separate generator, is introduced to a contactor where it mixes with the wastes and reacts with oxidizable species present.

4.3.6.2 Status

Conventional, undemonstrated.

4.3.6.3 Feasibility and Effectiveness

General Features

Ozonation is applicable only to dilute wastes, typically containing less than 1 percent oxidizable materials. The destructive power to refractory compounds may be enhanced by combining ozonation with ultra-violet radiation (Prengle et al., 1975). Ozone is generated at low concentrations (less than 2 percent) in an air stream, at slightly less than atmospheric pressure. Higher ozone concentrations are possible if oxygen is used as the gas supply.

Ozonation is effective with:

- chlorinated hydrocarbons
- alcohols
- chlorinated aromatics
- pesticides
- cyanides

Large contactors are required because reaction rates are mass transfer limited; ozone has only limited solubility in water. Contactor depth is typically on the order of 5 meters (16 ft) to insure adequate mixing and reaction time. Ultra-violet lamps, if used, are operated within the contactor vessel.

Ozone is corrosive, requiring special construction materials. Suitable materials include:

- stainless steel
- unplasticized PVC
- aluminum
- Teflon^R
- chromium-plated brass or bronze.

Special Precautions and Limitations

Ozone is acutely toxic; personnel safety is, therefore, a major concern. Modern systems are completely automated. An ozone monitor measures ozone levels in the gaseous effluent and reduces the ozonator voltage or frequency if gaseous levels exceed a preset limit (usually 0.05 ppm). An ambient air monitor sounds an alarm and shuts off the ozonator in the event of leaks of ozonized air. An off-gas ozone destruction unit is also generally used in modern systems.

4.3.6.4 Design Basis

Key design parameters include:

- Ozone dose rate -- usually expressed as either ppm ozone or pounds of ozone per pound of stream contaminants treated. Typical dose rates are 10 to 40 ppm for the former and 1.5 to 3.0 pounds per pound of contaminant removed for the latter (ADL, 1976).
- Retention time -- typical retention times range from 10 minutes to 1 hour in several stages.
- Ultra-violet light dosage -- expressed in terms of watts per liter. Dosage should be determined by laboratory studies. Typical dosage ranges from 1 to 10 watts per liter (Prengle, et al., 1975).

4.3.6.5 Principal Data Requirements

Leachate daily, average and variations in the flow (volume)

Concentration of oxidizable leachate analysis constituents in the leachate

Treatability study (laboratory-scaled)

Ozone dosage

Ultra-violet light dosage

Retention time

Operating temperature

4.3.6.6 Elements of Cost Review

Components

Construction and Capital--

- ozonator

- diesel generator
- pumps
- monitoring instrumentation

O & M----

- UV lamp replacement
- electricity

Major Factors

- process size
- ozone requirements

Data

Unit and total annual costs (in 1982 dollars) are estimated to be .77$/1000 gal and $228,000 for an ozonation system capable of treating (ADL, 1976):

- 800,000 gallons per day;
- reducing influent phenol concentration of 0.38 ppm to 0.012 ppm; and
- output 190 pounds of ozone per day.

4.4 PHYSICAL TREATMENT

4.4.1 Reverse Osmosis

4.4.1.1 Description

Reverse osmosis removes contaminants from aqueous wastes by passing the waste stream, at high pressure, through a semi-permeable membrane. At sufficiently high pressure, usually in the range 200-400 psi, clean water passes out through the membrane leaving a concentrated waste stream which must be treated further or disposed of. The high pressure counteracts the osmotic pressure of the dissolved wastes and acts as a driving force to concentrate the solution, hence the name reverse osmosis. Typical membranes are impermeable to most inorganic species and some organic compounds. They are also impermeable to very fine particles and will remove these as well as dissolved materials. The filtering action of membranes is conventionally termed ultrafiltration.

4.4.1.2 Status

Conventional, undemonstrated.

4.4.1.3 Feasibility and Effectiveness

General Features

Reverse osmosis (RO) and ultrafiltration take place in a cross-flow configuration. As the waste flows through a membrane tube or bundle, the purified water flows out at right angles through the membrane. This is different from conventional filtration where the waste flow goes directly through the filter medium, trapping materials on the upstream side. The cross-flow arrangement permits high flow rates through the system.

There are three basic configurations for RO systems:

- Tubular: perforated stainless steel or porous fiberglass tubes with liners of RO membrane, having the "active" side facing inwards. Water is pumped at high pressures through the tubes, and the cleaned water is collected outside the tube.
- Spiral wound or wrap cell: a flat sheet of membrane material is wound in a spiral to produce a continuous thin channel through which the feed flows at high laminar shear rates.
- Hollow fiber technologies: a bundle of hollow polyamide (nylon) fibers with the "active" side of the nylon membranes on the exteriors. Feedwater passes at high velocities between the fibers and fresh water is collected within the fibers.

Typical operating characteristics of a RO module design are summarized in Table 4-20.

Figure 4-17 shows an illustration of various RO configurations.

Reverse osmosis is capable of removing greater than 90 percent of TDS from wastewater streams containing up to 50,000 mg/l TDS. Organics with molecular weight in excess of 300 to 500, such as pesticides, can be removed at efficiencies exceeding 90 percent. Operation is sensitive to wastewater pH, TSS levels and TDS levels.

The choice of membrane material, as well as configuration, is critical to the functioning of an RO system. Cellulose acetate membranes are the most common, but many others have been introduced in recent years (see Table 4-21). Each material has a unique set of characteristics such as cost, ease of fabrication, serviceability, and resistance to variations in pH, temperature, and other stream parameters.

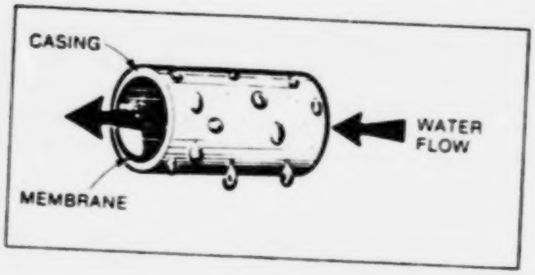
Special Precautions and Limitations

Pretreatment is often required to handle the following condition:

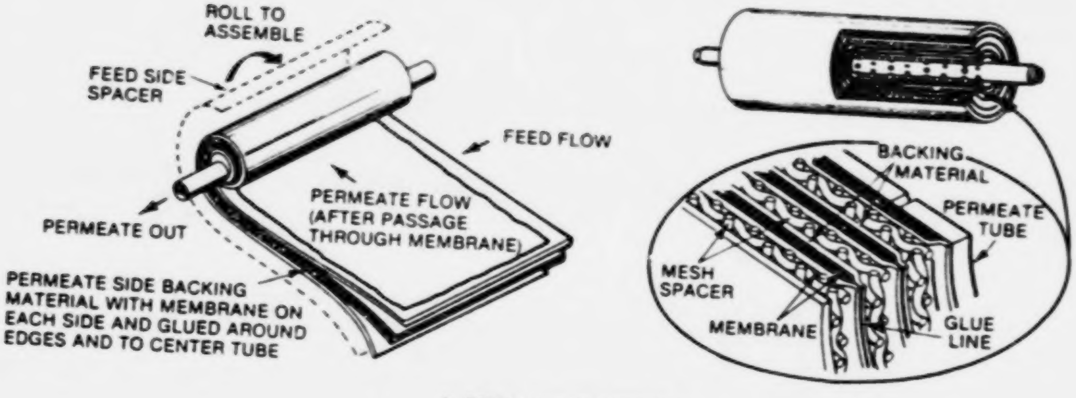
- Leachate variability -- Rapidly changing leachate properties such as pH, temperature and suspended solids concentration can limit membrane life requiring frequent replacement. Leachate equalization prior to the RO treatment should be considered if highly variable conditions exist.
- Leachate pH -- Because membrane operation is limited to certain pH ranges, pH adjustment should precede RO operation if necessary.
- Biological Organisms -- Living organisms in leachate can form films on RO membranes which reduces permeability. Such organisms should be destroyed by chlorination or ozonation prior to RO treatment.
- TSS -- Total suspended solids can plug RO modules, particularly the hollow fiber type. Suspended solids should be minimized to particle sizes less than about 10 microns prior to introduction in most RO modules.

FIGURE 4-17
MEMBRANE MODULE CONFIGURATIONS

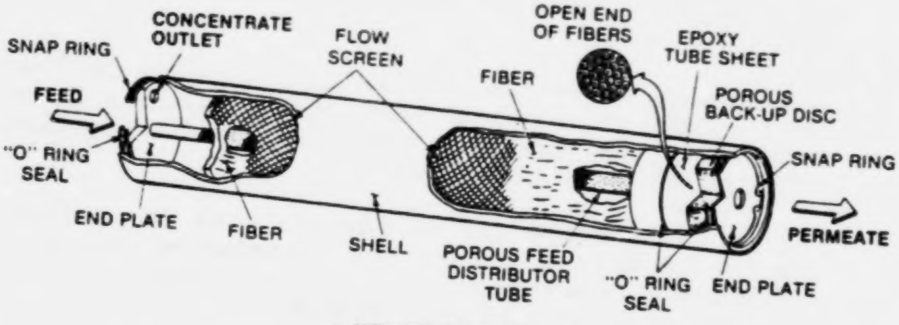
(Source: Ghassemi, et al., 1981)


CASING
WATER FLOW
MEMBRANE

a. TUBULAR MEMBRANE


ROLL TO ASSEMBLE
FEED SIDE SPACER
FEED FLOW
PERMEATE FLOW (AFTER PASSAGE THROUGH MEMBRANE)
PERMEATE OUT
PERMEATE SIDE BACKING MATERIAL WITH MEMBRANE ON EACH SIDE AND GLUED AROUND EDGES AND TO CENTER TUBE
BACKING MATERIAL
PERMEATE TUBE
MESH SPACER
MEMBRANE
GLUE LINE

b. SPIRAL-WOUND MODULE


CONCENTRATE OUTLET
SNAP RING
FLOW SCREEN
OPEN END OF FIBERS
EPOXY TUBE SHEET
FIBER
POROUS BACK-UP DISC
FEED
"O" RING SEAL
SNAP RING
END PLATE
FIBER
SHELL
POROUS FEED DISTRIBUTOR TUBE
"O" RING SEAL
END PLATE
PERMEATE

c. HOLLOW-FIBER MODULE

TABLE 4-20

COMPARISION OF REVERSE OSMOSIS MODULE CONFIGURATION

	Spiral wrap	Tubular	Hollow fine fiber
Membrane surface area per volume, ft^2/ft^3	100 - 300	40 - 100	5,000 - 10,000
Product water flux, gpd/ft^2	8 - 25[a]	8 - 25	0.1 - 2
Typical module factors:			
Brine velocity, ft/sec	[b]	1.5	0.04
Brine channel diameter, in	0.03[c]	0.5	0.004
Method of membrane replacement	As a membrane module assembly - on site	As tubes - on site	As entire pressure module - on site, module returned to factory
Membrane replacement labor	Low	High	Medium - requires equipment
High pressure limitation	Membrane compaction	Membrane compaction	Fiber collapse
Pressure drop, product water side	Medium	Low	High
Pressure drop, feed to brine exit	Medium	High	Low
Concentration polarization problem	Medium	High	High
Membrane cleaning - mechanical	No	Yes	No
- chemical	Yes - pH and solvent limited	Yes - pH and solvent limited	Yes - less restricted
Particulate in feed	Some filtration required	No problem	Filtration required

[a] Product flux varies with the net driving pressure and temperature; a flux of 10-25 gpd/ft^2 is typical at a pressure of about 400 psi.

[b] It is difficult to define velocity in a spiral element since the space between membrane is filled with a polypropylene screen which acts as a spacer and turbulent promoter.

[c] Height of brine channel (not diameter).

[d] Permissible pH and temperature ranges dependent primarily on membrane type and not on module configuration; for example, polyamide hollow fine fiber is pH limited from 4 to 11, cellulose acetate from 3 to 7.5, thin film composite (TFC) spirals have been operated and cleaned at pH levels ranging from 1 to 12.

Source: Ghassemi, et al., 1981

TABLE 4-21
REVERSE OSMOSIS MEMBRANE MATERIALS

- Used in General Practice
  - Cellulose Acetates
  - Cellulose Triacetate
  - Polyamides (Nylons)
  - Polysulfones
- Less Common or Developmental
  - Cellulose Acetate/Nitrate
  - Aromatic Polyhydrazines
  - Polybenzimidazolene (PBIL)
  - Polybenzimidazole (PBI)
  - Polyepimine/Amide
  - Polyepiamine/Urea
  - Sulfonated Polyfurane
  - Polyethyleneamine/Urea
  - Polypiperazine Isophthalamide
  - Polyacrylonitrile

- Residual chlorine -- Because chlorine will oxidize polyamide membranes, dechlorination is required.

4.4.1.4 Design Basis

Major design basis factors are:

- flow (gpd),
- solvent flux (g/cm^2)(sec))
- solute flux (g/(cm^2)(sec))

Flow rates are dictated by the quantity of leachate which must be treated daily at the site.

Solvent flow through the RO membrane is a function of the pressure applied to the RO membrane leachate treatment system and the osmotic pressure difference between the solution at the membrane interface and the permeate. The equation to calculate flux is:

$$J = K\ (\Delta P - \Delta\pi)$$

where:

J = solvent flux $(g/(cm^2)(sec))$

K = constant characteristic of membrane type and operating temperature $(g/cm^2)(sec)(atm))$

ΔP = applied pressure (atm) - pressure on permeate side of membrane (atm)

$\Delta\pi$ = osmotic pressure of solution - osmotic pressure of permeate (atm)

Solute flux through the RO membrane can be calculated as follows:

$$F = \beta(C_H - C_L)$$

where:

F = solute flux $(g/(cm^2)(sec))$

β = solute permeability coefficient (cm/sec)

C_H = solute concentration on high pressure side of membrane (g/cm^3)

C_L = solute concentration on low pressure side of membrane

Because solute flux is not a function of operating pressure, higher applied pressure will produce purer solvent permeate. Most membrane modules are operated at pressures between 350 to 600 psi. Operation at higher pressures may cause an increase in solute flux due to concentration polarization effects. However, continued operation at higher pressures may compact the membrane causing a decrease in flux. Flux decreases through the system as osmotic pressure increases. At some point, it will become more cost-effective to use an alternative technique to reduce TDS further, if needed.

4.4.1.5 Principal Data Requirements

Leachate analysis (general design data):

- hydraulic load
- TDS in solution
- osmotic pressure of solution
- solution pH
- solution temperature
- presence of oxidizing agents in solution

Treatability study (laboratory and pilot-scale)

- membrane and module type
- operating pressure
- solvent flux
- solute flux

4.4.1.6 Elements of Cost Review

Components

Construction and Capital--

- RO unit
- high pressure pump(s)

O & M--

- membrane replacement
- electricity

Major Factors

- RO unit size
- membrane replacement rate

Data

A cost example (unit and total) for a 3,280 gallon per day RO system for nickel plating line rinse water are given in Table 4-22.

The nickel concentration in the influent is 2250 ppm and is reduced to 20 ppm in the effluent. Ninety-four percent of the water is passed through the system, and the effluent is recycled in the rinse tank.

4.4.2 Equalization/Detention

4.4.2.1 Description

Equalization/detention smoothes fluctuations in waste quantity flow or in waste composition. Equalization conventionally refers to composition smoothing; detention to flow smoothing. Storage in tanks (surge tanks) or ponds is used to average flow or concentration over a period longer than the characteristic fluctuations. Reducing variability in the waste stream avoids potential upsets of downstream treatment processes, and may reduce costs.

4.4.2.2 Status

Conventional, demonstrated.

TABLE 4-22
ESTIMATED REVERSE OSMOSIS PLANT COSTS

Basis: 3,280 gpd; 330 days/year operation

Estimated Investment: $19,400

	Annual Quantity	Cost Per Unit Quantity, 1982 $	Annual Cost 1982 $
Variable Costs			
Labor & Maintenance (1/4 hr/day)	82.5 MH	$19.60/MH	1,600
Electricity	10.725 kWh	$ .04/kWh	400
Membrane Replacement (@ 2.5 yrs)			800
Total Variable Cost			2,800
Fixed Costs			
Capital Recovery (10% - 10 yrs)			3,100
Total Costs			5,900
Unit Costs ($/1000 gal)			$5.45

Source: ADL, 1976

4.4.2.3 Feasibility and Effectiveness

General Features

The two basic operating modes are:

- in-line equalization -- all flow passes through the equalization basin.
- off-line equalization -- only the flow above the average daily flow-rate is diverted to the equalization basin, and at low flow fed back into the main stream

In addition to sufficient volume to accommodate fluctuations, storage vessels must be well-mixed. Common mixing methods are (Adams and Eckenfelder, 1974):

- baffling;
- turbine mixing; and
- aeration.

Power requirements for surface aerator to achieve adequate mixing are a minimum of 15-20 hp/million gallons (Adams and Eckenfelder, 1974).

4.4.2.4 Special Precautions and Limitations

None noted.

4.4.2.5 Design Basis

Equalization/detention design is based on:

- Leachate influent variation(S_i')
- Probability of exceeding the maximum allowable contamination level for treated effluent (S_e')

These parameters are derived statistically from measurements of influent and effluent variation. Equations for these parameters are:

$$S_i' = \sigma^2 = \left(\sum_{i}^{\eta} (X_i - \bar{X})^2 \right) /(n-1)$$

where:

$\bar{X}$ = average influent contaminant concentration
$\bar{X}_i$ = influent contaminant concentration of sample i
η = number of samples

and

$$S_e' = \left(\frac{X_{max} - \bar{X}}{Y}\right)^2$$

where:

X_{max} = maximum effluent contaminant concentration allowable

$\bar{X}$ = average effluent contaminant concentration

Y = confidence factor (i.e., $Y \cong 1.65$ for 95% confidence that effluent concentration will not exceed X_{max} 95% of the time)

Detention time is calculated as follows:

$$t = \frac{\Delta t(S_i')}{2(S_e')}$$

where:

t = detention time

Δt = time interval of composite sample collection

Equalization/detention volume capacity is calculated as follows:

$$V = tF$$

where:

t = detention time

F = leachate flow

4.4.2.6 Principal Data Requirements

Statistics of leachate flow and concentration:

- influent samples (a minimum of 80) gathered at a regular frequency over a representative leachate flow period (a minimum of ten times the time scale of unacceptable fluctuations) (see Adams and Eckenfelder, 1974).

4.4.2.7 Elements of Cost Review

Components

Construction and Capital--

- basin construction
- pumps
- mixers
- aeration equipment

O & M--

- electricity

Major Factors

- basin size
- mixing and/or aeration requirements

Data

Sample costs for several different capacity equalization facilities are given in Table 4-23.

TABLE 4-23
COSTS OF EQUALIZATION FACILITIES

Plant Size mgd	Basin Size Mgal	Earthen Basin		Concrete Basin	
		With Pumping	Without Pumping	With Pumping	Without Pumping
1	0.32	$276,400	$161,000	$389,700	$276,400
3	0.88	222,400	186,700	741,500	549,800
10	2.40	707,900	298,900	1,734,000	1,325,000

Source: Research and Education Assoc., 1978

4.4.3 Ion Exchange

4.4.3.1 Description

Ion exchange is a reversible interchange of ions between an insoluble salt or resin, in contact with wastes containing ionic species. In the process, unwanted ionic species, principally inorganic, are replaced (exchanged) with innocuous ions on the resin. For instance, if a solution containing the salt M^+X^- flows over a cation exchange material(R^-) containing a cation N^+, then the following reversible reaction occurs:

$$M^+ + X^- + R^- + N^+ \rightleftarrows R^-M^+ + N^+ + X^-$$

Because the reaction is reversible, it is possible to regenerate the ion exchange resin. The overall process yields two output streams; one main purified product stream, containing N^+ and X^-, and a small solution of the "spent" regenerant, containing a high concentration of the removed ions, (e.g., M^+).

4.4.3.2 Status

Conventional, demonstrated.

4.4.3.3 Feasibility and Effectiveness

General Features

Most inorganic dissolved salts and some organic dissolved salts can be removed by ion exchange. Removal efficiencies for metallic ions are generally very high, as shown in Table 4-24, displaying data for a typical metal-containing electroplating waste.

Removal efficiency is limited by the exchange equilibrium which is expressed for the general reaction previously described as follows:

$$K = \frac{R^{-}M^{+}[N^{+}]}{R^{-}N^{+}[M^{+}]}$$

where:

K = equilibrium (selectivity coefficient) which is specific for the type of resin and the solution character

$N+$ = concentration of the sacrificial resin ion species

$R^{-}N^{+}$ = mole fraction of the removed cation on the exchange resin

$R^{-}N^{+}$ = mole fraction of the resin sacrificial cation on the exchange resin

M^{+} = concentration of the removal object cation

Other chemical classes which can be removed are:

- inorganic anions (halides, sulfates, nitrates, and cyanide);
- organic acids (carboxyl, sulfonics, some phenols at sufficiently alkaline pH);
- amines, when pH is low enough to form the acid salt; and anionic and cationic species (quaternary amines and alkylsulfates).

TABLE 4-24
REMOVAL DATA FOR ELECTROPLATING WASTEWATER STREAMS

Pollutant/parameter	Concentration, μg/l		Percent removal
	Influent	Effluent	
Toxic pollutants:			
Cadmium	5,700	BDL[a]	>99
Chromium	3,100	10	>99
Chromium (+6)	7,100	10	>99
Copper	4,500	90	98
Cyanide	9,800	40	99
Nickel	6,200	BDL	>99
Silver	1,500	BDL	>99
Zinc	15,000	400	97

[a] Below detectable limits; assumed to be <10 μ/l

Source: EPA, 1980

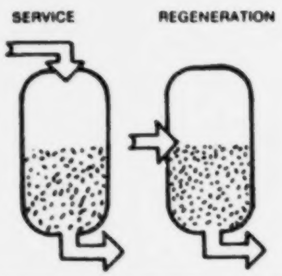
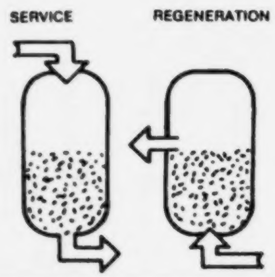
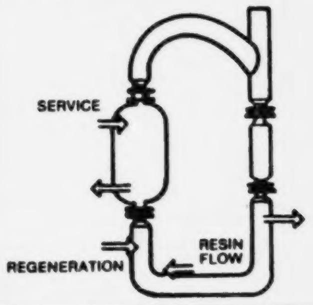
Resins can be grouped into the following four major types:

- strong acids which remove cations in general;
- weak acids which remove cations of strong bases;
- strong bases which remove anions in general; and
- weak bases which remove anions of strong acids.

Theoretically, ion exchange processes are capable of treating TDS concentrations up to 10,000 to 20,000 mg/l. However, practical operations are limited to TDS concentrations less than 2,500 mg/l because of the excessive service requirements associated with resin regeneration at higher TDS concentrations (TRD 5).

There are three principal ion exchange system configurations as shown in Table 4-25.

TABLE 4-25
ION EXCHANGE SYSTEM

Types	Cocurrent Fixed Bed  	Countercurrent Fixed Bed  	Continuous Countercurrent 
Description of Process	Downflow of raw fluid to be treated (loading phase). Upflow backwash. Downflow regeneration. Downflow rinse. Batch loading and regeneration.	Regeneration flows opposite in direction to influent. Backwash (in regeneration) does not occur on every cycle to preserve resin stage heights. Resin bed is locked in place during regeneration.	Multi-stage countercurrent movement of resin in closed loop providing simultaneous treatment, regeneration, backwash and rinse. Operation is only interrupted for momentary resin pulse.
Indications for Use	Low loads (200 PPM in softening; 250 TDS in demin). Lower thruput (about 1000 GPM). Where regeneration chemical cost is not critical, disposal of waste volume in large single batch not critical, and dilution of feed no problem. Manual operation acceptable.	Handles high loads at moderate thruput or low loads at high thruput (GPM x TDS or GPM x PPM removal = 40,000 or more). Where effluent quality must be relatively constant, regeneration cost is relatively critical, disposal of single batch waste volume no problem.	Highloads with high thruputs (GPM x TDS or GPM x PPM removal = 40,000 or more). Where constant effluent quality is essential, regeneration costs critical, total waste volume requires small, concentrated stream to be controllable. Where loss of product thru dilution and waste must be minimized. Where available floor space is limited.
Advantages	Low capital cost. Automatic controls instrumentation optional. Simple, basic type of unit. Easy maintenance.	Moderate capital cost. Can be operated with periodic attention. Moderate regeneration cost. Lesser volume of waste due to less frequent backwash. Consistent effluent quality.	Lowest regeneration cost. Lowest resin inventory. Consistent effluent quality. Highest thruput to floor space. Large capacity units factory preassembled. Concentrated low-volume waste stream. Can handle strong chemical solutions and slurry. Fully automatic operation.
Disadvantages	High regenerant cost. Fluctuating effluent quality. Large single batch waste disposal. High water consumption thru dilution and waste. Requires substantial floor space.	Increased controls and instrumentation, higher cost. Requires mechanism to lock resin bed. Large single batches of waste disposal. Moderate water consmption thru dilution and waste. Requires substantial floor space.	Requires automatic controls and instrumentation, higher capital cost. More headroom required.

Source: Ghassemi, et al., 1981

Special Precautions and Limitations

Operational effectiveness can be reduced by suspended solids clogging the resin bed and/or organics fouling the resin surface. Influents should be analyzed for these parameters and appropriate pretreatment measures taken if necessary.

4.4.3.4 Design Basis

Important design parameters include:

- resin selection to remove pollutants of concern;
- flow rate of leachate to be treated; and
- column flow-through rate which is expressed as linear flow

  $$\left([\text{gal}] / [(\text{min})(\text{ft}^2)]\right) \text{ or volume flow } \left([\text{gal}] / (\text{min})(\text{ft}^3)\right)$$

  to be used in the process. Laboratory studies are necessary to optimize column flow-through rates. The laboratory experiments should utilize columns with a minimum inner diameter of one inch and a bed depth which approximates that which will be used in field operations. Typical operational bed depths range from 1 to 3 meters. Full scale operations can be scaled directly from laboratory results as long as bed depth is held constant. Operation flow rates generally range from 15 to 80 bed volumes per hour. If bed depth is increased up to a factor 2, the overall system performance improves; and
- regeneration rate required to keep system operating within effluent specifications. Laboratory experiments are used to determine the effluent pollutant concentration versus number of bed volumes of solution treated. During regeneration, column flow-through rates typically range from .5 to 5 bed volumes per hour. The resin is usually backwashed before regeneration to prevent a build-up of solids in the resin. Effective backwashing requires a 50 percent bed expansion for 15 to 20 minutes

4.4.3.5 Principal Data Requirements

Leachate daily average and variations in flow rate:

- leachate analysis (resin selection)
- TDS concentration levels and identity
- TSS concentration

Treatability study (laboratory scale)

- column flow-through rate
- resin regeneration frequency

4.4.3.6 Elements of Cost Review

Components

Construction and Capital--

- exchanged columns
- exchange resins
- pumps
- tanks

O & M--

- resin regeneration or replacement
- electricity

Major Factors

- process size

Data

A cost example (unit and total costs) for an 80,000-gallon per day ion exchange system is presented in Table 4-26.

4.4.4 Carbon Adsorption

4.4.4.1 Description

Carbon adsorption removes contaminants from aqueous wastes by contacting the stream with a solid, activated carbon adsorbent in granular (most common) or powdered form. Organic compounds, and some inorganic species become bound to the surface of the carbon particles (adsorption) and are subsequently removed along with the adsorbent.

4.4.4.2 Status

Conventional, demonstrated.

4.4.4.3 Feasibility and Effectiveness

General Features

Carbon adsorption is used primarily to remove organic compounds not treatable by biological treatment. This process is often used as a polishing step following biological treatment. The combination of the two processes appears to be a cost-effective method for removal of a wide range of organics from aqueous wastes.

Carbon adsorption technology is applicable to dissolved organics, generally. Many organics can be reduced to the one to ten μg/l level. Results of an EPA study showed that 51 of 60 toxic organic compounds could be removed (EPA, 1980). Some inorganic species, such as antimony, arsenic, bismuth, chromium, tin, silver, mercury, and cobalt are partially absorbed (EPA, 1982). Conventional water quality parameters (BOD, COD, TOC) are also reduced by carbon adsorption; the performance level is dependent on the specific waste stream characteristics.

TABLE 4-26
ION EXCHANGE COST ESTIMATES

Basis: 80,000 gallons/day
24 hour/day --- 350 days/year
3 bed system, in duplicate for regeneration
24-hour loading time

Capital Investment: $648,000

Variable Cost	Annual Quantity	Cost Per Unit Quantity, 1982 $	Annual Cost 1982 $
Operating Labor	2,200 MH	$19.60/MH	$ 43,100
Chemicals			
Resin Replacement (20%/yr)			4,200
- NaOH (70%)	175 tons	350.00/ton	61,200
- H_2SO_4 (98%)	48 tons	83.90/ton	4,000
Total Chemicals			$ 69,400
Utilities (Electricity)	75,000 kWh	.04/kWh	3,000
Maintenance (3% of Inv.)			19,400
Total Variable Costs			$134,900
Fixed Costs			
Taxes & Insurance (2% Inv.)			$ 13,000
Capital Recovery (10 years @ 10%)			104,800
Total Fixed Costs			$117,800
Total Costs			$252,700
Unit Costs ($/$10^3$ gallons)			$ 9.03

Source: ADL, 1976

Although there is no theoretical, technical upper limit for the concentration of adsorbable organics in the waste stream; economics in conventional systems generally dictate a practical limit of about one percent. Hazardous wastes, quite frequently, contain organics in excess of one percent. Even so, carbon adsorption may be cost-effective since the economic premises for remedial action are very different from those of conventional wastewater treatment.

The removal process configuration for the two forms of carbons is quite different.

- Granular Activated Carbon -- Contact between the adsorbent and the waste stream occurs in a moving bed reactor or in fixed bed reactors coupled in several possible configurations as shown in Figure 4-18.

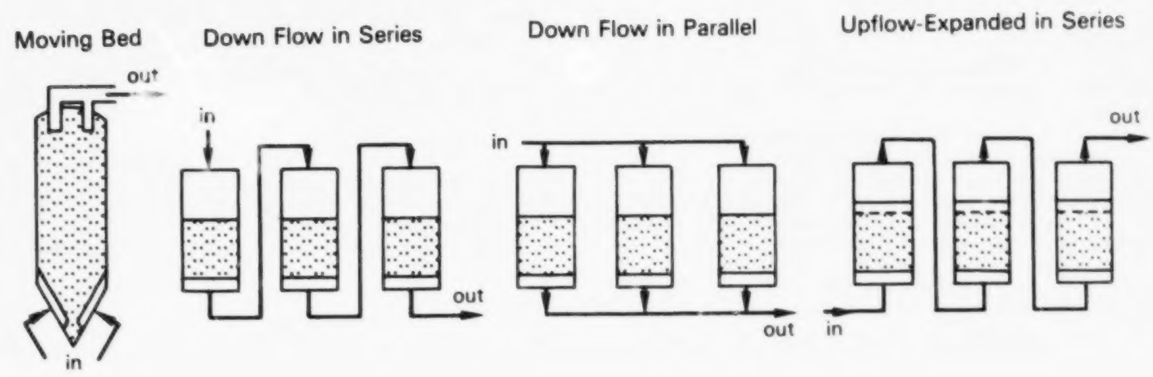
  Periodically, when the carbon adsorption capacity is exhausted, fresh or regenerated carbon is added, replacing the spent adsorbent. The used carbon is removed for disposal, destruction or regeneration.

- Powdered Activated Carbon -- Finely ground carbon is mixed with the wastewaters, and, after sufficient time for the adsorption to occur, is removed and disposed of. The powdered form of carbon is not regenerated. The carbon is generally added to the clarifier of the biological treatment system, but may alternatively be added directly to a sludge aeration tank. The spent carbon containing the adsorbed contaminants is removed along with the excess sludge. Powdered carbon may improve the settleability of the sludge in addition to its primary adsorbent function. A combined activated sludge, powdered activated carbon system is capable of reducing BOD and COD levels which would, normally, overload a conventional activated sludge system (EPA, 1980).

The choice of system configuration for both granular and powdered carbon depends on many factors. Table 4-27 presents a summary of the primary determinants. The flow direction depends on the specific application. Downflow systems can accommodate higher suspended solids concentrations (i.e., 65-70 mg/l) if the liquid viscosity is similar to that of water. Solids are filtered out and the column requires periodic backwashing. Upflow systems can handle more viscous liquids and require less bed washing. The most commonly used contact method is a flow-through column system.

FIGURE 4-18

GRANULAR ACTIVATED CARBON SYSTEM CONFIGURATION
(Source: ADL, 1976)


Moving Bed
Down Flow in Series
Down Flow in Parallel
Upflow-Expanded in Series
out
in
in
out
in
out
in
out

- Counter-current carbon use
- Prior suspended solids removal
- Small volume systems

- Counter-current carbon use
- Maximum linear velocity
- Large volume systems

- Filtration and adsorption capability
- Maximum linear velocity
- Large volume systems

- Counter-current carbon use
- Minimum head loss
- Minimum pretreatment

TABLE 4-27
CONTACTING SYSTEMS

Method	Application Conditions	Comments
Single or parallel adsorbers	·Pollutant breakthrough curve is steep. ·Carbon recharge interval is long. ·Volume flow is high. ·Influent is viscous.	·Typical flows are 1 to 4gpm/ft^2. ·Parallel system is usually selected if pressure drop problems are expected for the system. ·Moderate adsorbent expense.
Adsorbers in series	·Pollutant breakthrough curve is gradual. ·Uninterrupted operation is necessary. ·Relatively low effluent concentration is required. ·Carbon recharge interval is short.	·Typical flows are 3-7gpm/ft^2. ·High adsorbent expense.
Expanded upflow adsorber(s)	·For high flows and high suspended solids concentrations.	·Typical flows are 5-9gpm/ft^2. ·Suspended solids are passed through the column and not separated.
Moving bed	·For systems requiring efficient use of carbon (i.e., carbon adsorption capacity is exhausted before removal from column).	·Influent must contain less than 10mg/l TSS, and not biologically active. Either parameter will cause a pressure drop in the system and necessitate removal of carbon prior exhaustion of its absorption capacity.
Powdered carbon with subsequent clarifier and/or filter	·Carbon useage higher than for series of fixed-bed adsorbers. ·Influent concentration of pollutants should be relatively constant to avoid frequent sampling and adjustment of carbon dosage.	·No restrictions or suspended solids or oil and grease in influent. ·Capital equipment costs relatively low. ·Simple to operate.
Powdered activated carbon with activated sludge	·For activated sludge systems receiving toxic or shock organic loadings.	·Protects the biological system from toxic organics and shock loadings. Generally improves effluent quality.

Source: ADL, 1976

Regeneration of spent carbon may be accomplished by a variety of means, the most common involving thermal destruction of the adsorbed organics in a multiple hearth furnace. About 5 to 10 percent of the carbon is lost in this (and most other) regeneration process due to the creation of fines from the mechanical handling of the carbon. Other regeneration processes include thermal treatment with steam, extraction of adsorbed organics with solvents (including acids, bases, and super critical fluids), and biological degradation of the adsorbed material.

Special Precautions and Limitations

Carbon adsorption system performance is sensitive to the composition of the influent and flow variations. Because a system design based on good data can perform poorly if influent conditions change, systems are generally oversized. If influent composition is expected to vary significantly, an equalization tank preceding the carbon adsorption system may be necessary. For fixed-bed, granular carbon systems special attention must be given to the materials of construction (to prevent corrosion and mechanical failure) and to the materials handling equipment (pipes, pumps, valves, controls) for the transfer of carbon to and from various tanks and/or regeneration units.

Care must be taken to insure that the adsorption capacity of the carbon is not reduced either by chemicals, resins, or fine precipitates in the influent, or by the continued presence of similar chemicals in the residual water (after draining) if the carbon is thermally regenerated. In the latter case, any material (e.g, inorganic salts, some resins) that are not volitalized or combusted during regeneration will remain in the pores of the carbon resulting in an irreversible loss of adsorption capacity.

In all cases, it is prudent to consider the possibility of biological activity in the carbon system. Such activity can help (via pollutant biodegradation) or hinder (via clogging and/or odor generation) the process. Suspended solids and oil/grease can interfere with carbon adsorption treatment. Influent concentrations of these pollutants should not exceed 50 ppm and 10 ppm, respectively (ADL, 1976).

4.4.4.4 Design Basis

The type of activated carbon to be used is a primary design consideration. Several commercial carbons are available. The products differ in physical properties such as pore size, surface area, and adsorption characteristics. Some commercial carbons are listed in Table 4-28.

Carbon selection requires laboratory testing of carbon adsorption capacities for the specific waste stream to be treated. Both equilibrium adsorption isotherms and carbon column breakthrough curves should be determined.

For adsorption isotherms, the general test procedure is to mix batches of wastewater with quantities of activated carbon and analyze the equilibrium conditions. If the full-scale treatment system will include carbon regeneration, then activated carbon which has been regenerated several times should be used. If virgin carbon is used, then a carbon with undersized pore size could be selected because carbon surface area associated the smaller pores and pure volumes are reduced by regeneration (Schweitzer, 1979). Laboratory results of the pollutant adsorbed to carbon ratio (wt/wt basis) are plotted against the pollutant equilibrium concentration (mg/l) on log/log paper as shown in Figure 4-19. Temperature and pH effects can be studied with this experimental technique. Based on the graphical comparison of adsorption efficiencies, the appropriate carbon type can be chosen to meet effluent criteria.

Design parameters are a function of the organic load, hydraulic load, contact method, and contact time. A summary of contact methods and their typical operation applications is provided in Table 4-28.

It is not possible to use carbon adsorption isotherms to predict full-scale contactor behavior. Contactor design must be optimized by laboratory testing, conventionally using a method known as bed-depth/service time analysis (BDST) (Adams and Eckenfelder, 1974). Typically, three to four columns of equal bed depth are operated in series. Bed depths usually range from 4 ft to 20 ft. Hydraulic load rates should simulate field operating conditions which are usually 2-10 gpm/ft^2. Effluent from each column is analyzed for a target parameter such as total organic carbon (TOC). The effluent-to-influent adsorbable TOC concentration ratio is plotted as a function of bed volumes treated, as shown in Figure 4-20. The data shown in Figure 4-20 can be represented as service time versus bed depth for various removal efficiency levels as shown in Figure 4-21.

TABLE 4-28
PROPERTIES OF SEVERAL COMMERCIALLY AVAILABLE CARBONS[a]

PHYSICAL PROPERTIES	ICI AMERICA HYDRODARCO 3000	CALGON FILTRASORB 300 (8x30)	WESTVACO NUCHAR WV-L (8x30)	WITCO 517 (12x30)
Surface area, m^2/gm (BET)	600-650	950-1050	1000	1050
Apparent density, gm/cc	0.43	0.48	0.48	0.48
Density, backwashed and drained, lb/cu ft	22	26	26	30
Real density, gm/cc	2.0	2.1	2.1	2.1
Particle density, gm/cc	1.4–1.5	1.3–1.4	1.4	0.92
Effective size, mm	0.8–0.9	0.8–0.9	0.85–1.05	0.89
Uniformity coefficient	1.7	1.9 or less	1.8 or less	1.44
Pore volume, cc/gm	0.95	0.85	0.85	0.60
Mean particle diameter, mm	1.6	1.5–1.7	1.5–1.7	1.2
SPECIFICATIONS				
Sieve size (U.S. std. series)				
Larger than No. 8 (max. %)	8	8	8	c
Larger than No. 12 (max. %)	c	c	c	5
Smaller than No. 30 (max. %)	5	5	5	5
Smaller than No. 40 (max. %)	c	c	c	c
Iodine No.	650	900	950	1000
Abrasion No., minimum	b	70	70	85
Ash (%)	b	8	7.5	0.5
Moisture as packed (max. %)	b	2	2	1

[a] Other sizes of carbon are available on request from the manufacturers.

[b] No available data from the manufacturer.

[c] Not applicable to this size carbon.

Source: ADL, 1976

FIGURE 4-19

SCHEMATIC OF CARBON ADSORPTION ISOTHERM

(Source: Adams and Eckenfelder, 1974)

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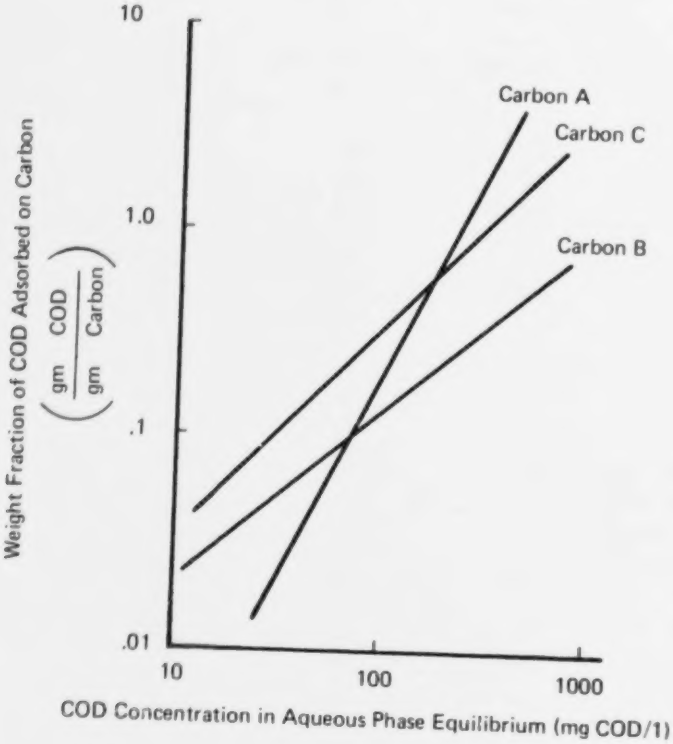

The full-scale system can be designed based on the BDST data. Because BDST results are sensitive to hydraulic load rate and pollutant concentration levels, these parameters should reflect anticipated field conditions in the testing program. A series system is sized so that as the first column's adsorptive capacity is exhausted, the effluent from the last column is approaching the defined pollutant limitations. For a moving bed system where 5 percent of the carbon should be periodically removed, total bed depth is designed so that as the bottom 5 percent of the carbon is exhausted, the effluent is approaching the defined pollutant limitations. A sample sizing calculation for a moving bed system and a series system based on the BDST curves is shown in Figure 4-21.

The carbon usage rate is equal to the service time multiplied by the quantity replaced following each servicing. For example, carbon use for a series system is calculated by:

FIGURE 4-20

SCHEMATIC BREAKTHROUGH CURVES FOR COLUMNS IN SERIES

(Source: Adams and Eckenfelder, 1974)

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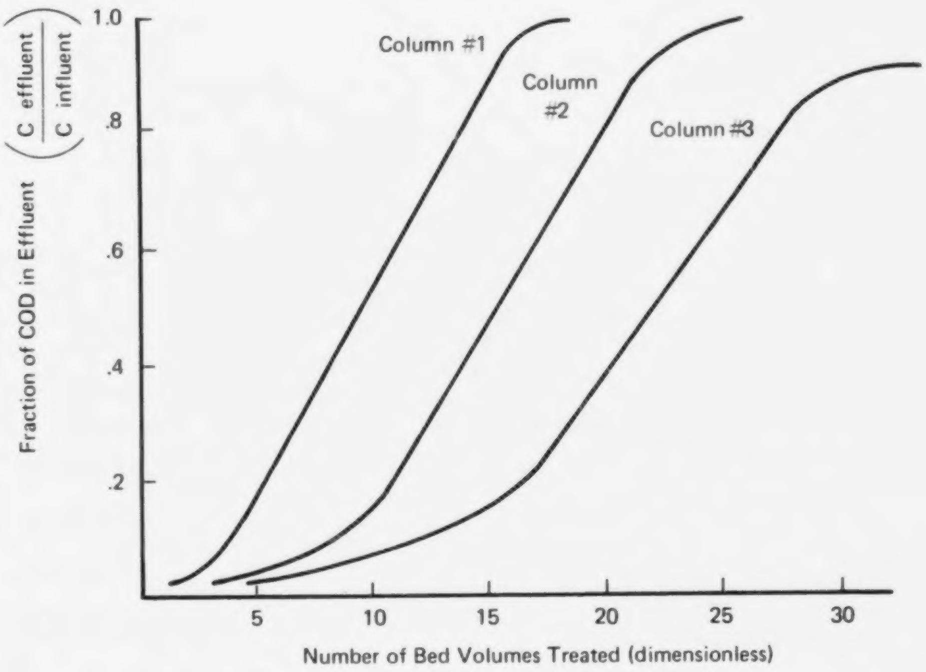


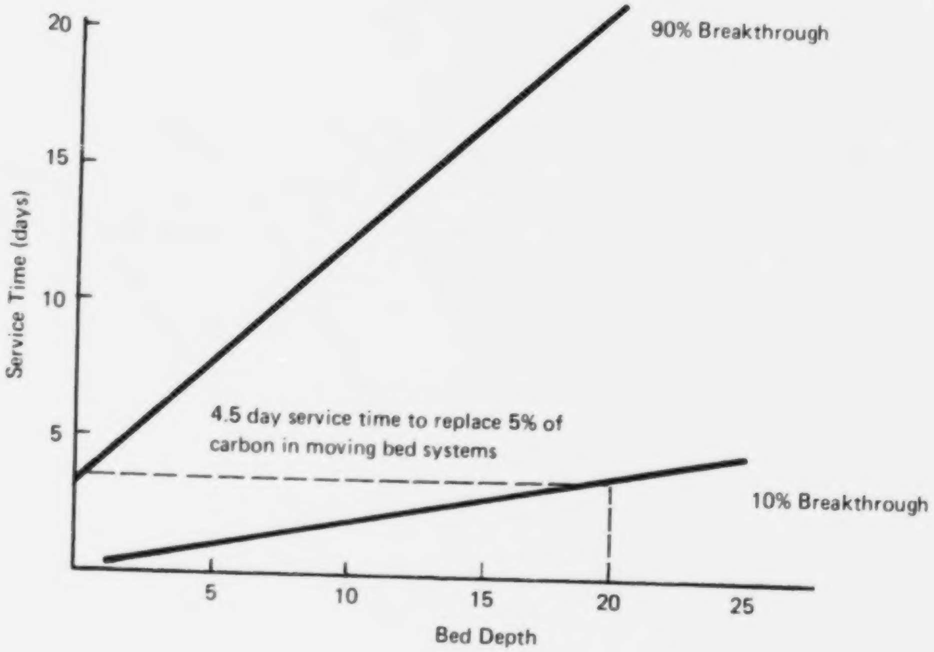
$$\text{Carbon usage (lb/day)} = \frac{\text{Column vol(ft}^3\text{) x Carbon density (lb/ft}^3\text{)}}{\text{Service period (day)}}$$

If carbon usage rates exceed 1,000 pounds per day, the regeneration of the carbon is generally more economic than disposal or destruction options. Thermal methods are usually used to regenerate the carbon; multiple hearth furnaces are most commonly used. Sizing depends on the quantity of carbon regenerated. Examples of carbon regeneration rates for multiple hearth furnaces are (Adams and Eckenfelder, 1974):

FIGURE 4-21

SCHEMATIC OF BED DEPTH VERSUS SERVICE TIME

(After: Adams and Eckenfelder, 1974)



- 3.5 (lb/hr-ft^2) for regeneration of industrial carbon application; and
- 4.7 (lb/hr-ft^2) for regeneration of municipal treatment carbon application.

Regeneration rates may vary considerably for specific treatment applications. The regeneration capacity required can be calculated by dividing the carbon recharge quantity by the service interval as follows:

$$\text{Regeneration capacity} = \frac{\text{Carbon charge (lb)}}{\text{Service time (hr)}}$$

It is common practice to specify a regeneration capacity up to twice the amount actually needed in order to allow for unscheduled maintenance.

4.4.4.5 Principal Data Requirements

Leachate daily average flow rate (bed cross-sectional area)

Leachate analysis (service time)

- influent concentrations

Carbon selection (batch equilibrium adsorption isotherm tests)

- carbon loss during one regeneration cycle (if regeneration is included in design)
- physical properties, bulk density

Bed depth - service time (BDST) (laboratory column tests)

- hydraulic loading (flow per unit area) usually 2-8 gpm/ft^2.
- organic removal rate
- backwash hudraulic loading (if backwashing is included in design)
- adsorption efficiency
- adsorption rate constant

4.4.4.6 Elements of Cost Review

Components

Construction and Capital--

- carbon columns

- reactivation equipment
- pumps

O & M--

- carbon regeneration and/or replacement
- electricity

Major Factors

- process size
- carbon exhaustion rate

Data

Construction and O & M costs are shown in Figures 4-22 and 4-23, respectively.

A cost example for a 100,000 gallon per day carbon adsorption unit designed to treat influent containing 1,000 ppm phenol is given in Table 4-29.

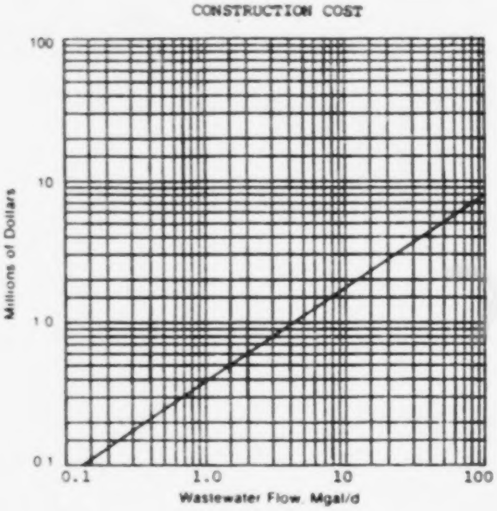
4.4.5 Stripping

4.4.5.1 Description

Stripping removes volatile contaminants from an aqueous waste stream by passing air or steam through the wastes. With air, the volatile, dissolved gases are transferred to the air streams for treatment such as carbon adsorption or thermal oxidation. With steam the process is, in essence, a steam distillation of the waste with the volatile contaminants ending up in the distillate for treatment. Typical system configurations are shown in Figures 4-24 and 4-25.

FIGURE 4-22

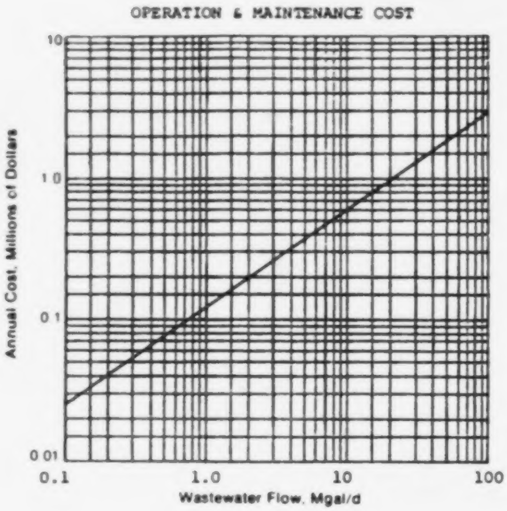
CONSTRUCTION COSTS FOR TERTIARY ACTIVATED CARBON TREATMENT (1976 COSTS)[a]
(Source: EPA, 1982)



[a] to adjust costs to 1982 dollars, multiply by 1.62.

FIGURE 4-23

O&M COSTS FOR TERTIARY ACTIVATED CARBON TREATMENT (1976 COSTS)[a]
(Source: EPA, 1982)



[a] to adjust costs to 1982 dollars, multiply by 1.74.

TABLE 4-29
ESTIMATED COSTS FOR ACTIVATED CARBON REMOVAL OF PHENOL

Basis: 100,000 gpd, 1,000 ppm Phenol; 330 days/yr operation.

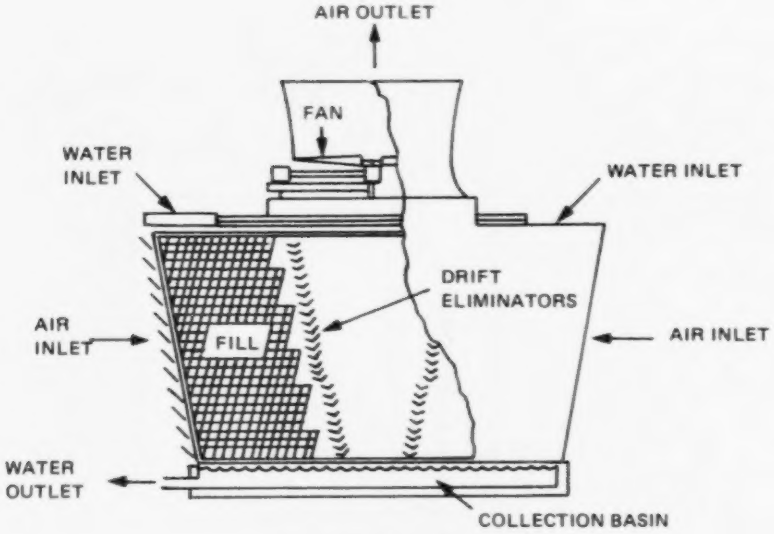
Estimated Investment: $1,944,000

Variable Costs	Annual Quantity	Cost Per Unit Quantity, 1982 $	Annual Cost 1982 $
Labor	11,500 MH	$19.60/MH	$225,400
Maintenance (5% of Inv)			97,200
Electricity	700×10^3 kWh	.04/kWh	28,000
Steam	2.35×10^6 lb	$7.50/10^3$ lb	17,600
Fuel	17.5×10^9 Btu	$5.00/10^6$ Btu	87,500
Make-up Carbon	174×10^3 lb	1.00/lb	174,000
Total Variable Costs			$692,700
Fixed Costs			
Taxes and Insurance (2% of Inv)			$ 38,900
Capital Recovery (10%-10 yrs)			315,900
Total Fixed Costs			$354,800
Total Costs			$984,500
Unit Cost - ($/1000 gallons)			$29.83
Unit Cost - ($/lb of Phenol)			$3.58

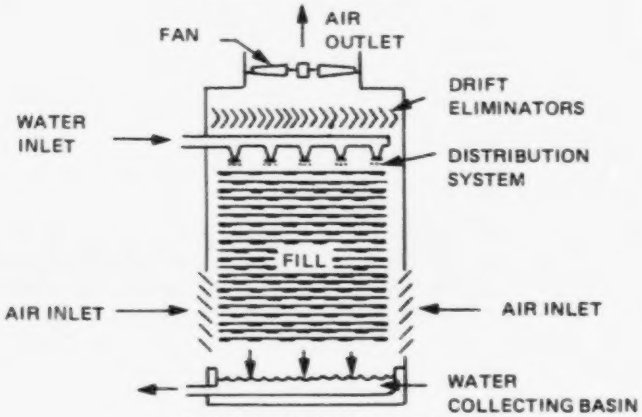
Source: ADL, 1976

FIGURE 4-24

AIR STRIPPING TOWERS
(Source: EPA, 1982)


AIR OUTLET
FAN
WATER INLET
WATER INLET
DRIFT ELIMINATORS
AIR INLET
FILL
AIR INLET
WATER OUTLET
COLLECTION BASIN

CROSS-FLOW TOWER


AIR OUTLET
FAN
DRIFT ELIMINATORS
WATER INLET
DISTRIBUTION SYSTEM
FILL
AIR INLET
AIR INLET
WATER COLLECTING BASIN

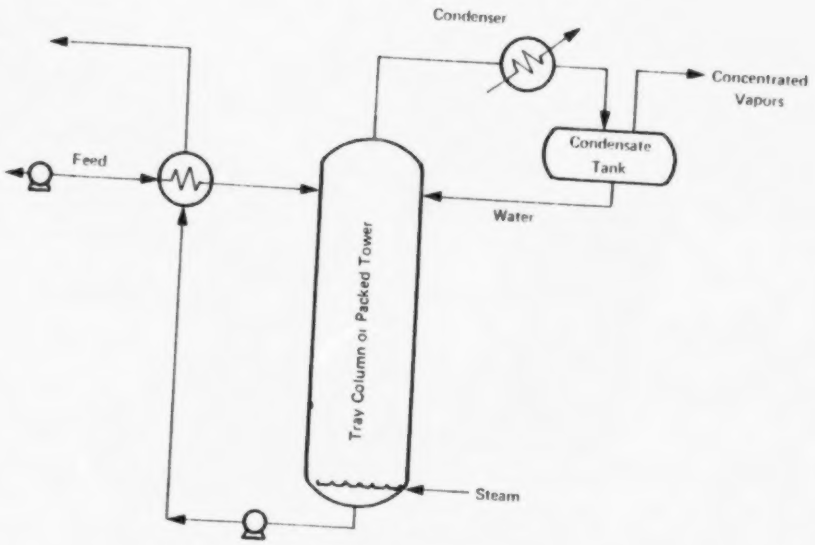
COUNTERCURRENT TOWER

4.4.5.2 Status

Conventional, demonstrated. Air stripping has been used for trihalomethane and TCE removal.

4.4.5.3 Feasibility and Effectiveness

FIGURE 4-25
TYPICAL STEAM STRIPPING SYSTEM
(Source: ADL, 1976)


Condenser
Concentrated Vapors
Condensate Tank
Feed
Water
Tray Column or Packed Tower
Steam

General Features

Both versions of stripping are capable of high removal efficiencies. Air stripping of ammonia from wastewaters has exceeded 90 percent for influent ammonia concentrations of less than 100 ppm (ADL, 1976), and 99+ percent has been achieved for removal of TCE from groundwater.

Steam stripping can be applied to:

- volatile organic compounds (phenol, vinyl chloride, etc.)
- water-immiscible compounds (chlorinated hydrocarbons, etc.)
- ammonia

- hydrogen sulfide

Removal efficiencies of volatile organic compounds from wastewaters ranging from 10 percent to 99 percent have been reported (EPA, 1980).

Special Precautions and Limitations

Air stripping has been demonstrated only for ammonia in cooling tower systems.

Both air and steam stripping pose potential air pollution problems if volatile organic compounds are present in the leachate. Air pollution problems can be prevented by using emission control devices (e.g, condenses, carbon adsorption filters) and maintaining proper operating conditions in the system.

4.4.5.4 Design Basis

Design parameters for air and steam stripping are site specific. The following design specifications are presented for illustrative purposes.

- Air Stripping (ADL, 1977)

  Hydraulic Load: 40 l/mm/m^2 (gpm/ft^2)

  Air Flow: 3 m^3/l (400 ft^3/gal)

  Depth of "Packing": 8 m (25 ft)

  Operating Temperature: 16 - 40°C

  Operating Wastewater pH: 11 - 12

  Treatment Levels (effluent criteria)

- Steam Stripping (EPA, 1980)

  Wastewater Flow: 760 l/min (200 gpm)

  Steam Requirement: .07 - .24 kg/l (0.6 - 2.0 lb/gal)

Column Height: 6 - 18 m
Colum Diameter: 1 - 3 m

4.4.5.5 Principal Data Requirements

Air Stripping

Leachate daily average and peak flow (column length)

Leachate analysis (gas flow)

- temperature
- strippable component concentration

Column or tower packing characteristics (manufacturer's data)

- pressure drop
- height of transfer unit

Steam Stripping

Same as for air stripping.

4.4.5.6 Elements of Cost Review

Components

Construction and Capital--

Air

- packing tower

- fans
- rapid mix tanks
- pumps

Steam

- packing tower
- reboiler
- reflux condenser
- tank(s)
- pump(s)
- heat exchanger

O & M--

- steam
- electricity
- cooling water

Major Factors

- process size
- process size
- steam requirements

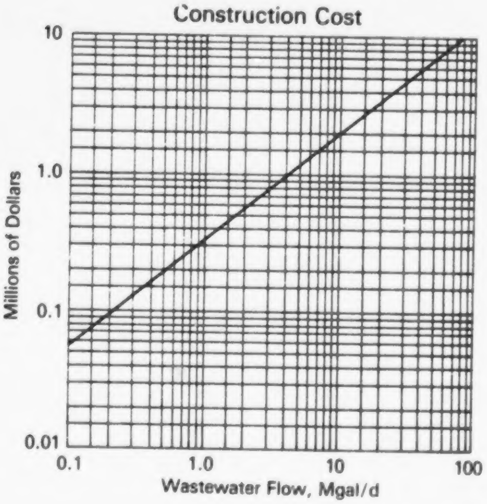
Data

Capital and operating cost for an ammonia stripping unit are shown in Figures 4-26 and 4-27, respectively.

Capital and operating cost are given for a 200-gallon per day steam stripper are shown in Tables 4-30 and 4-31, respectively.

FIGURE 4-26

CAPITAL COSTS OF
AMMONIA STRIPPING SYSTEM
(Source: EPA, 1982)

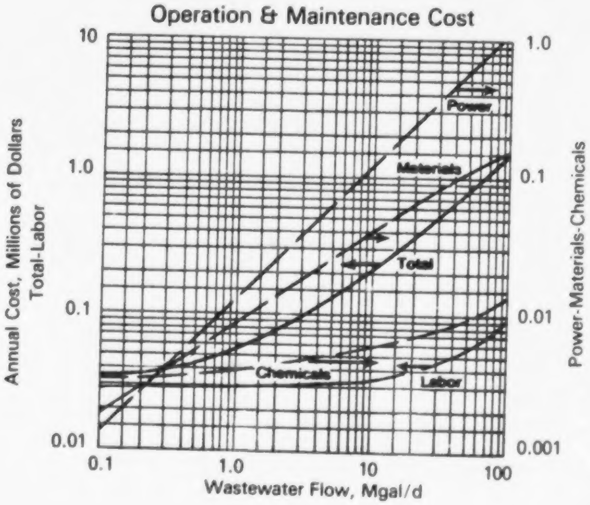


Includes: Related Yardwork; Engineering, Legal, Fiscal, and Financing Costs During Construction, and Excluding Cost of pH Adjustment. Based on 1 gpm/sf of Tower Packing, 24 ft Packing Depth. Includes Influent Pumping (TDH = 50 ft).[a]

[a] to update costs to 1982 dollars, multiply by 1.62.

FIGURE 4-27

OPERATION AND MAINTENANCE COSTS
OF AMMONIA STRIPPING SYSTEM
(Source: EPA, 1982)



Excludes: Cost of pH Adjustment; Labor Fixed @ 59/hour, Power @ $0.02/kWh.[a]

[a] to update costs to 1982 dollars, multiply by:
labor—1.64
power—2.0
materials—1.52

TABLE 4-30
CAPITAL INVESTMENT FOR A 200 GPM STEAM STRIPPER [a]

	Purchased Equipment 1982 $
Feed Pump 200 gpm @130 ft head	$ 6,280
Feed Pump 200 gpm @ 60 ft head	2,830
Feed Heat Exchanger 800 sq. ft.	31,400
Distillation Column 24 trays, 6 ft. diameter x 60 ft.	219,800
Condenser - 400 sq ft	18,800
Condensate Tank - 1,000 gal	6,280
Total Purchased Equipment	$285,400
Total Capital Investment	$1,377,000

[a] All equipment 304 stainless steel.

Source: ADL, 1976

4.4.6 Sedimentation

4.4.6.1 Description

Sedimentation removes suspended hazardous components from aqueous solution by permitting the particles to settle to the bottom of a vessel through the action of gravity.

4.4.6.2 Status

Conventional, demonstrated.

4.4.6.3 Feasibility and Effectiveness

TABLE 4-31
OPERATING COSTS FOR A 200 GPM SOUR WATER STEAM STRIPPER

Basis: - 200 gpm sour water containing 5% by weight $(NH_4)_2S$.
- 350 days/yr, 24 hr/day.

Capital Investment: $1,377,000 - 100 MM gal/yr

Variable Costs	Annual Quantity	Cost Per Unit Quantity 1982 $	Annual Cost 1982 $
Operating Labor (2m-h/shift)	$ 2100	$ 19.60	$ 41,200
Steam	2×10^8 lb	7.50/1,000 lb	1,500,000
Electrical Energy	1.7×10^5 kWh	.04/kWh	6,800
Cooling Water	1.2×10^9 gal	.15/1,000 gal	180,000
Maintenance (5% of Inv.)			68,900
Total Variable Cost			1,796,900
Fixed Costs			
Capital Recovery (10 yrs at 10%)			223,600
Taxes and Insurance (at 2% cap. inv./yr)			27,500
Total Fixed Costs			$ 251,100
Total Operating Cost			$2,048,000
Unit Cost ($/1,000 gal)			$ 21.36

Source: ADL, 1976

General Features

Flocculating agents, producing agglomerates of individual free particles, are often used to enhance the settling action. In conventional industrial waste applications, sedimentation can reduce waste TSS loadings to 10 to 200 mg/l, corresponding to a removal efficiency of 90-99 percent for typical wastes. There is no limitation on influent concentrations in this method.

Operating modes are:

- Batch
- Continuous (most common)

Settling tanks generally have conical bottoms with sludge removal at the apex. Baffles are often installed to maintain quiescent conditions and prevent reentrainment of settling particles.

Design should include:

- adequate volume for surge flow
- adequate flocculation time (30-60 minutes)

Special Precautions and Limitations

None noted.

4.4.6.4 Design Basis

Key design factors are (Schweitzer, 1979):

- solids handling capacity or unit area (lb/[(hr)(ft^2)])
- overflow rate - typical loading rates are:
  - 500 - 600 gpd/ft^2 for alum treated wastewater

  - 700 - 800 gpd/ft^2 for iron treated wastewater
  - 1400 - 1600 gpd/ft^2 for lime treated wastewater
- retention time - velocity of wastewater through the sedimentation tank should be in the range of 0.5 and 3 ft/minute
- weir loading - typical loading rates are 10,000 - 40,000 gpd/ft (Metcalf and Eddy,1979)

4.4.6.5 Principal Data Requirements

Leachate daily average flow (area)

Settling velocity (area, through-put), laboratory study or can be estimated from leachate characteristics for particles greater than 0.02mm in diameter)(Schweitzer, 1979).

Leachate analysis (area, through-put)

- size distribution
- solids specific gravity
- liquid specific gravity

4.4.6.6 Elements of Cost Review

See Precipitation

4.4.7 Dissolved Air Flotation

4.4.7.1 Description

Dissolved air flotation removes insoluble hazardous components present as suspended fine particles or globules of oils and greases from an aqueous phase. In this technique aqueous waste mixtures are first saturated with air at high pressures and then moved into tanks under atmospheric pressure. The reduction of pressure causes small bubbles of air to form and rise to the surface. The rising bubbles carry the fine particles and small globules of oil or grease to the surface where they are skimmed off.

4.4.7.2 Status

Conventional, demonstrated.

4.4.7.3 Feasibility and Effectiveness

General Features

Flotation can be used on suspended wastes of density close to that of water (1.0 g/l). The addition of surface active chemicals and pH adjustment are often used to enhance the sweeping action of the bubbles and the skimming operation. In industrial practice, with wastes containing TSS and oil or grease levels up to 900 mg/l, removal efficiency of 90 percent has been recorded (EPA, 1980).

Special Precautions and Limitations

If the stream contains volatile organic constituents, air emissions resulting from stripping during the flotation process could become a problem and may require additional treatment controls, such as those used for air emission control.

4.4.7.4 Design Basis

Major design variables and corresponding operating conditions are (Adams & Eckenfelder, 1974):

- System pressure, 40-60 PSIG;
- Recycle flow, 30%-40% for oily waste;

$$R = \frac{Q\ (A^*/S)\ X_o}{C_s[f(P/14.7 + 1)-1]}$$

where:

R = recycle flow

Q = influent flow (mgd)

A^*/S = air supply to waste water solids ratio (lb/lb)

X_o = average influent suspended solids concentration (mg/l)

C_s = gas saturation at atmospheric conditions (mg/l)

f = fraction of theoretical saturation ($\sim$.80)

P = pressure (psi)

and:

$$A^* = R\, C_s\, [f(P/14.7 + 1) - 1](8.34)$$

- Hydraulic loading, 1-4 gpm/ft^2 ; and
- Retention period, 20-40 minutes.

It is common engineering practice to triple the calculated A* to provide a safety factor and excess air for high dissolution efficiency.

The hydraulic loading rate (referred to as surface loading rate (SLR)) is determined by plotting laboratory experimental values of effluent pollutant concentrations versus surface loading rates. The rate which is sufficient to achieve effluent water quality goals is identified from the graph.

The retention time equation is:

$$t = \frac{d}{SLR}$$

where a depth of 4 to 9 feet is typically chosen (EPA, 1980)

4.4.7.5 Principal Data Requirements

Required design information includes (Ad[illegible]nd Eckenfelder, 1974):

Leachate daily average flow (system volume)

Leachate temperature (recycle flow)

Leachate oil/grease or suspended solids concentration (recycle flow)

Treatability tests (air requirements, pressure)

  - rise rate
  - A*/S ratio
  - hydraulic loading rate (surface loading rate)

4.4.7.6 Elements of Cost Review

Components

Construction and Capital--

- flotation basin
- aerator
- pumps
- pressure tanks
- skimming equipment

O & M--

- electricity
- solids removal

Major Factors

- Surface area of flotation basin
- Hydraulic loading

Data

Capital cost for a dissolved air flotation system with a 200-square foot surface area is approximately $63,000 (1982 dollars)(Adams and Eckenfelder, 1974).

4.4.8 Filtration

4.4.8.1 Description

Filtration is a physical means of separating solids from liquids (and vice versa) by forcing the fluid through a porous medium. For hazardous waste, filtration can serve two separate objectives:

- removal of suspended solids from a liquid stream for the purpose of producing a purified liquid; or
- volume reduction of waste sludges by increasing the solids concentration by removing the liquid (sludge dewatering).

This discussion applies to particulates greater than 25 microns in diameter. Waste particulates greater than about 25 microns in diameter are trapped at the surface or within the porous filter medium as the fluids flow through. Smaller particles must be agglomerated. In all filtration systems pressure or suction is required to force the fluid through the filter, as is some means to remove the trapped solids.

4.4.8.2 Status

Conventional, demonstrated.

4.4.8.3 Feasibility and Effectiveness

General Features

Any liquid with filterable solids can be treated. Filtration is also applicable to aqueous liquids containing droplets of another immiscible liquid phase such as oil-contaminated water. Filtration is often used on sludges or liquids generated during other waste treatment processes.

There are three major filtration system types:

- granular media filter
- rotary drum vacuum filter
- filter press.

Granular media filters (Figure 4-28) are widely used for separating suspended solids from aqueous liquid streams. The granular media (usually sand or sand and coke) is contained in a basin equipped with an underdrain. Water drains through either by gravity or due to applied pressure. As the bed clogs with solids, the filter medium is backwashed, dislodging the solids, the backwashed water is a small volume of liquid from which solids can be removed by flocculation and/or sedimentation.

In rotary drum vacuum filters (Figure 4-29) the filter medium is a fabric or wire mesh belt stretched over a drum and a small roller. The drum is partially immersed in the liquid to be filtered. A vacuum applied to the inside of the drum draws the liquid through, and the liquid is collected from within; the solids trapped on the filter cloth are scraped off as the belt is rotated out of the liquid and past a scraping device.

A filter press (Figure 4-30) consists of a series of plates and screens. Referring to the figure, liquid is introduced in the "B" cavity; pressed against this cavity are plates "A" and "B" which are perforated metal sheets covered with a fabric filter medium. The plates and frames are pressed together forcing the liquid out of cavity "B" while trapping solids. Filter presses treat sludge of a similar nature to that treated by rotary drums. They also dewater gelatinous and sticky sludges which are often difficult to treat.

Table 4-32 shows the applicability of these different types of filtration systems to various waste forms.

FIGURE 4-28

GRANULAR MEDIA FILTER
(Source: ADL, 1976)

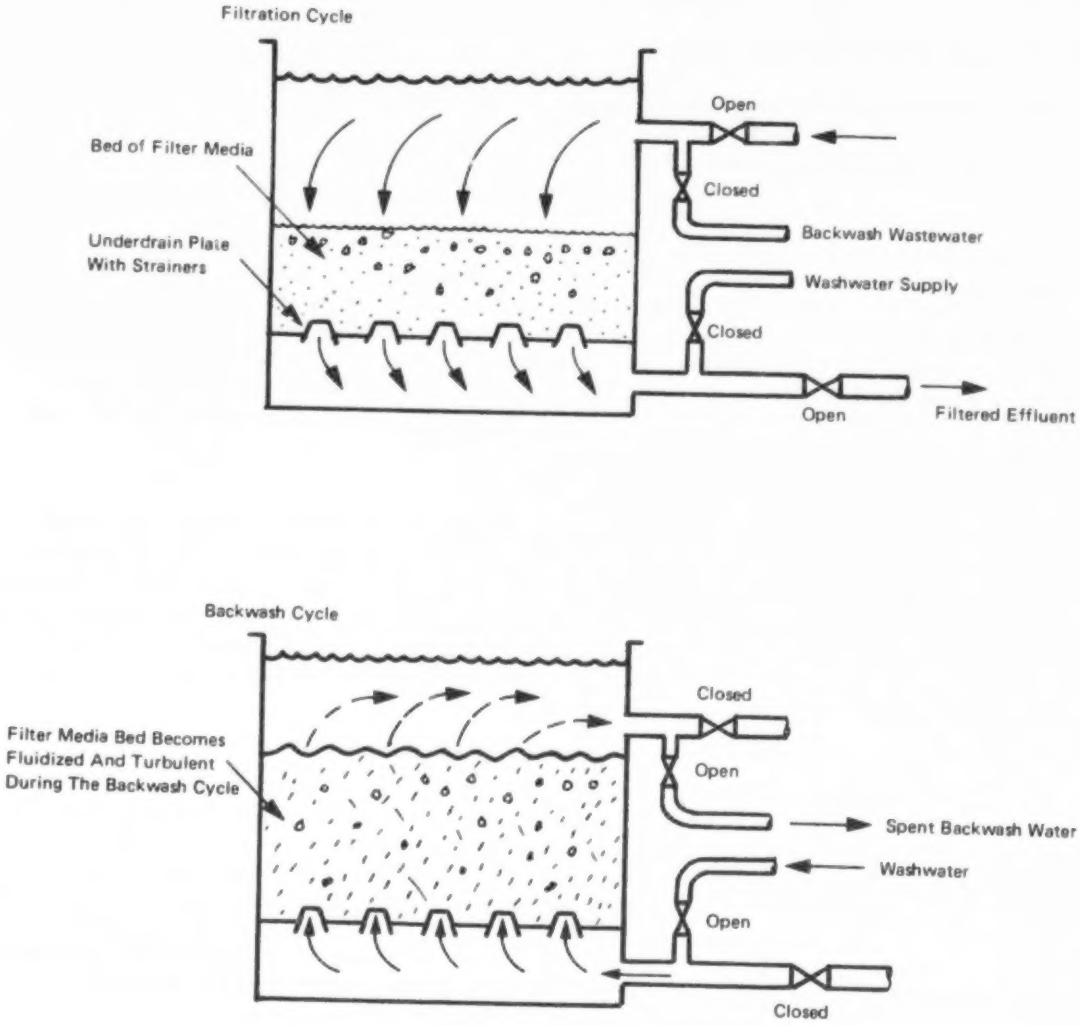
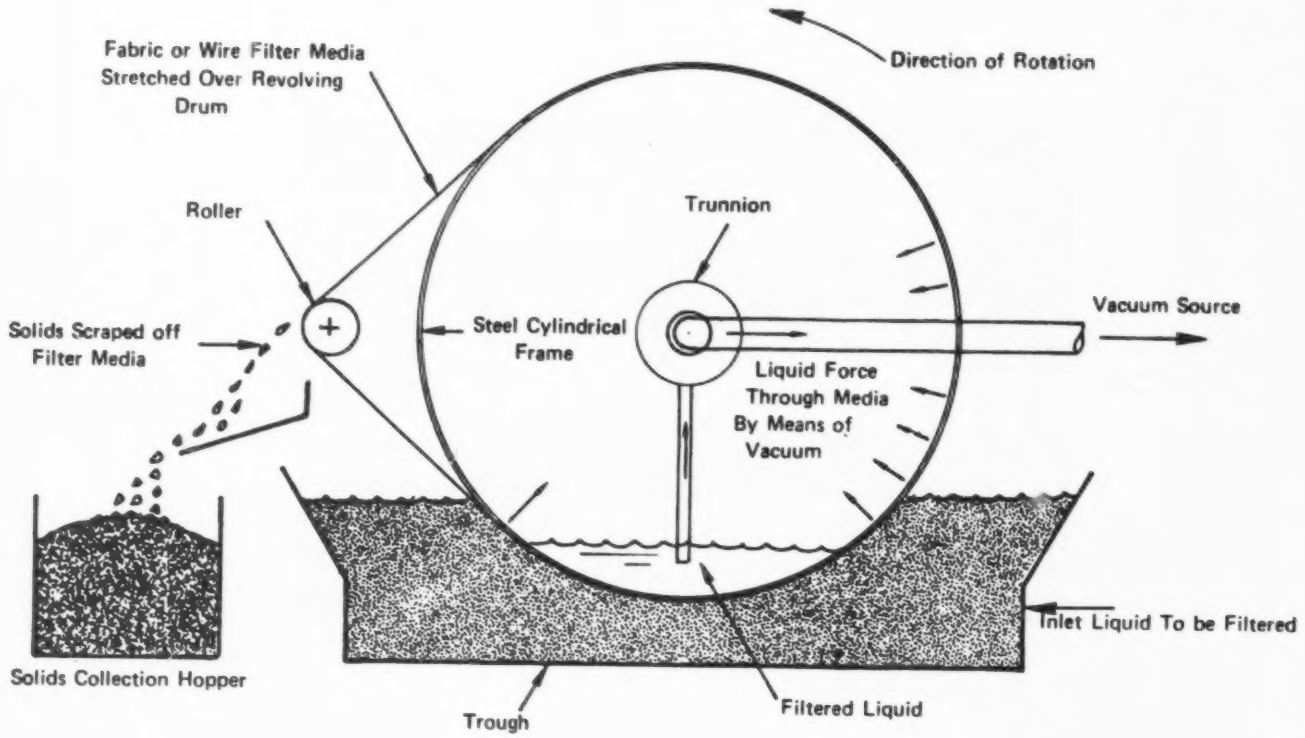

Filtration Cycle
Open
Bed of Filter Media
Closed
Backwash Wastewater
Underdrain Plate
With Strainers
Washwater Supply
Closed
Open
Filtered Effluent
Backwash Cycle
Closed
Filter Media Bed Becomes
Fluidized And Turbulent
During The Backwash Cycle
Open
Spent Backwash Water
Washwater
Open
Closed

FIGURE 4-29

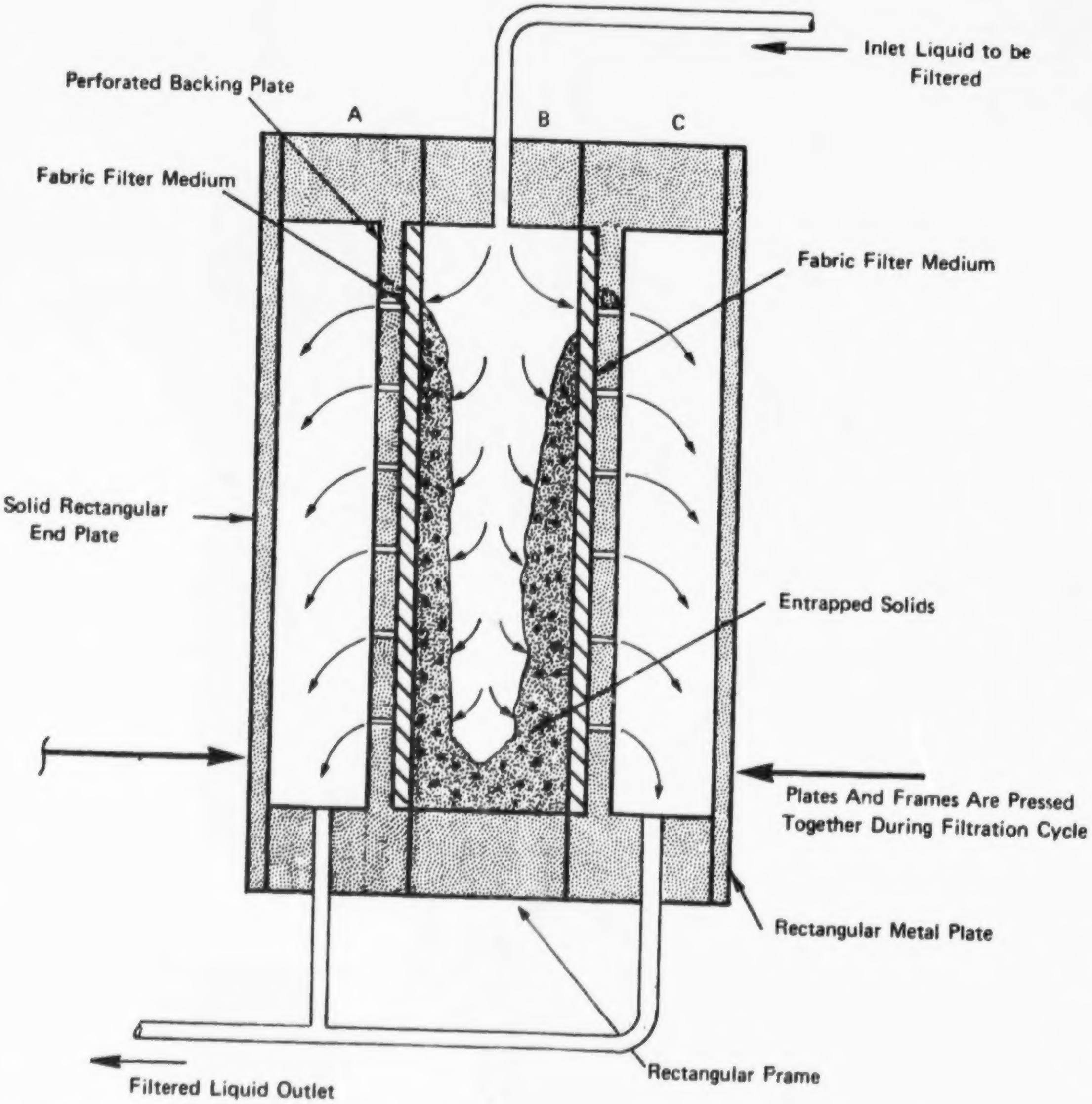
ROTARY DRUM VACUUM FILTER
(Cross-Sectional Side View)
(Source: ADL, 1976)



Fabric or Wire Filter Media Stretched Over Revolving Drum
Direction of Rotation
Roller
Trunnion
Solids Scraped off Filter Media
Steel Cylindrical Frame
Vacuum Source
Liquid Force Through Media By Means of Vacuum
Inlet Liquid To be Filtered
Solids Collection Hopper
Trough
Filtered Liquid

FIGURE 4-30

FILTER PRESS
(Illustrative Cross-Sectional View of One Rectangular Chamber)
(Source: ADL, 1976)


Inlet Liquid to be Filtered
Perforated Backing Plate
A
B
C
Fabric Filter Medium
Fabric Filter Medium
Solid Rectangular End Plate
Entrapped Solids
Plates And Frames Are Pressed Together During Filtration Cycle
Rectangular Metal Plate
Rectangular Frame
Filtered Liquid Outlet

When the cavity formed between plates A and C is filled with solids, the plates are separated.
The solids are than removed and the medium is washed clean.
The plates are than pressed together and filtration resumed.

TABLE 4-32
POTENTIAL APPLICABILITY OF FILTRATION
TO VARIOUS FORMS OF HAZARDOUS WASTES

Waste Form	Granular Media Filters	Rotary Drum Vacuum Filters	Filter Presses
Aqueous	High	High	High
Non-Aqueous Liquid	Moderate	Moderate/high	Moderate/high
Slurries	Low	High	High
Sludges	Low	High	High

Source: ADL, 1976

Table 4-33 shows typical operating conditions. Effluent characteristics are typically:

- Granular Filter Media -- suspended solids in effluent can be as low as 1-10 mg/l.
- Rotary Drum Vacuum Filter -- sludges dewatered to a solids concentration of 10-40 percent, filtrate still retains several thousand mg/l suspended solids.
- Filter Press -- sludges dewatered to 15-50 percent solids concentration; filtrate contains several thousand mg/l suspended solids.

Special Precautions and Limitations

Variability of solids content in remedial action applications may cause clogging and reduce the overall operating efficiency.

The liquid effluent from hazardous waste sludge dewatering may contain hazardous materials and then require treatment before disposal. Laboratory tests should be performed to determine the extent of this type of potential problem.

TABLE 4-33
MAJOR DESIGN AND PERFORMANCE VARIABLES FOR FILTRATION

	Granular Filter Media	Filter Presses	Rotary Drum Vacuum Filters
Solid Content-Influent (mg/L or % by weight)	<200	>2%	>2%
Pressure Differential	Usual gravity	17 atm	Vacuum
Waste Throughput	80-250 L/min/m^2	1-10 kg/m^2/hr (solids-drywt)	10-50 kg/m^2/hr (solids-drywt)

Source: ADL, 1976

4.4.8.4 Design Basis

Contact time is primary design parameter (Adams and Eckenfelder, 1974):

- Granular Media Filters -- run time of filter system cycle (initial to maximum allowable headloss) is calculated as follows:

$$T = \frac{\delta_t}{ds/dt} \quad \frac{694Q}{Q_A}$$

where:

T = time of filter run cycle
δ_t = total filter deposit (lb/ft^2)
ds/dt = rate of solids accumulation lb/hr)
Q = design flow rate (mgd)
Q_A = hydraulic loading rate (gpm/ft^2)

- Rotary Drum Filters -- the filtration time to volume of filtrate is calculated as follows:

$$\frac{t}{v} = \frac{\mu r c}{2\ PA^2}\ V + \frac{\mu R_m}{PA}$$

where:

t/v = filtration time/filtrate volume (sec/ml)
μ = filtrates viscosity (poise)
r = specific resistance (sec^2/g)
c = solids removed per volume of filtrate (g/ml)
P = applied vacuum (g/cm^2)
A = filtration area (cm^2)
R_m = initial resistance of the filter media (sec^2/cm^2)

- Filter Press -- design is based on quantity of filter cake produced and the volume of sludge processed per unit time.

4.4.8.5 Principal Data Requirements

Granular Media

Leachate daily average flow (filter area)

Leachate suspended solids concentration (length of run)

Performance tests (laboratory)

- solids removal rate
- head loss
- bed expansion/backwash

Filter media characteristics (manufacturer's data)

Rotary Drum Filter

Leachate daily average flow (filter area)

Leachate suspended solids concentration (filtration time, area)

Filterability tests (laboratory-funnel tests)

- conditioner effects
- specific resistance
- cake constant

Filter loading tests (laboratory scale)

- compressibility coefficient
- solids concentration exponent
- form time exponent

Filter Press

Leachate daily average flow (filter area)

Leachate suspended solids concentration (filter area, cycle time)

Filterability tests (laboratory scale)

- conditioner requirements
- cake resistance
- cake thickness

4.4.8.6 Elements of Cost Review

Components

Construction and Capital--

- filter
- pumps

O & M--

- electricity
- replacement of filter medium

Major Factors

- Surface area of filter medium

Data

A cost example (unit and total cost) is given in Table 4-34.

4.5 DIRECT TREATMENT

4.5.1 In Situ Leachate/Groundwater Treatment

4.5.1.1 Description

In situ leachate treatment introduces a reactant into the contaminated region to interact with the leachate plume. Two principal variations are:

- Permeable Treatment Beds -- This approach uses trenches filled with a reactive permeable medium to act as an underground reactor (see Figure 4-31). Contaminated groundwater or leachate entering the bed reacts to produce a nonhazardous soluble product or a solid precipitate.
- Chemical Injection -- This process entails injecting chemicals into the ground beneath the waste (see Figure 4-32) to neutralize, precipitate, or destroy the leachate constituents of concern.

4.5.1.2 Status

- Permeable Treatment Beds -- Developmental.
- Chemical Injection -- Conceptual.

TABLE 4-34
VACUUM FILTRATION COST ESTIMATES AS A FUNCTION OF SIZE
(1982 dollars)

	Treatment System Size		
	12,000 gpd (2 tpd solids)	36,000 gpd (6 tpd solids)	108,000 gpd (18 tpd solids)
Capital Investment	$166,900	$324,000	$626,900
Variable Cost			
Labor	37,600	58,800	91,400
Maintenance	5,000	9,700	18,800
Chemicals			
Quicklime	22	65	200
Ferric Chloride	450	1,300	4,000
Electrical Energy	2,000	6,300	18,600
Total Variable Cost	$ 45,100	$ 76,200	$133,000
Fixed Cost			
Capital Recovery	$ 27,200	$ 52,800	$102,200
Taxes and Insurance	3,300	6,500	12,500
Total Fixed Cost	$ 30,500	$ 59,300	$114,700
Total Annual Cost	$ 75,600	$135,500	$247,700
Unit Cost (cost per ton of dry solids processed)	$107.08	$ 62.37	$38.72

Source: ADL, 1976

FIGURE 4-31

INSTALLATION OF A PERMEABLE TREATMENT BED

(Source: EPA, 1982)

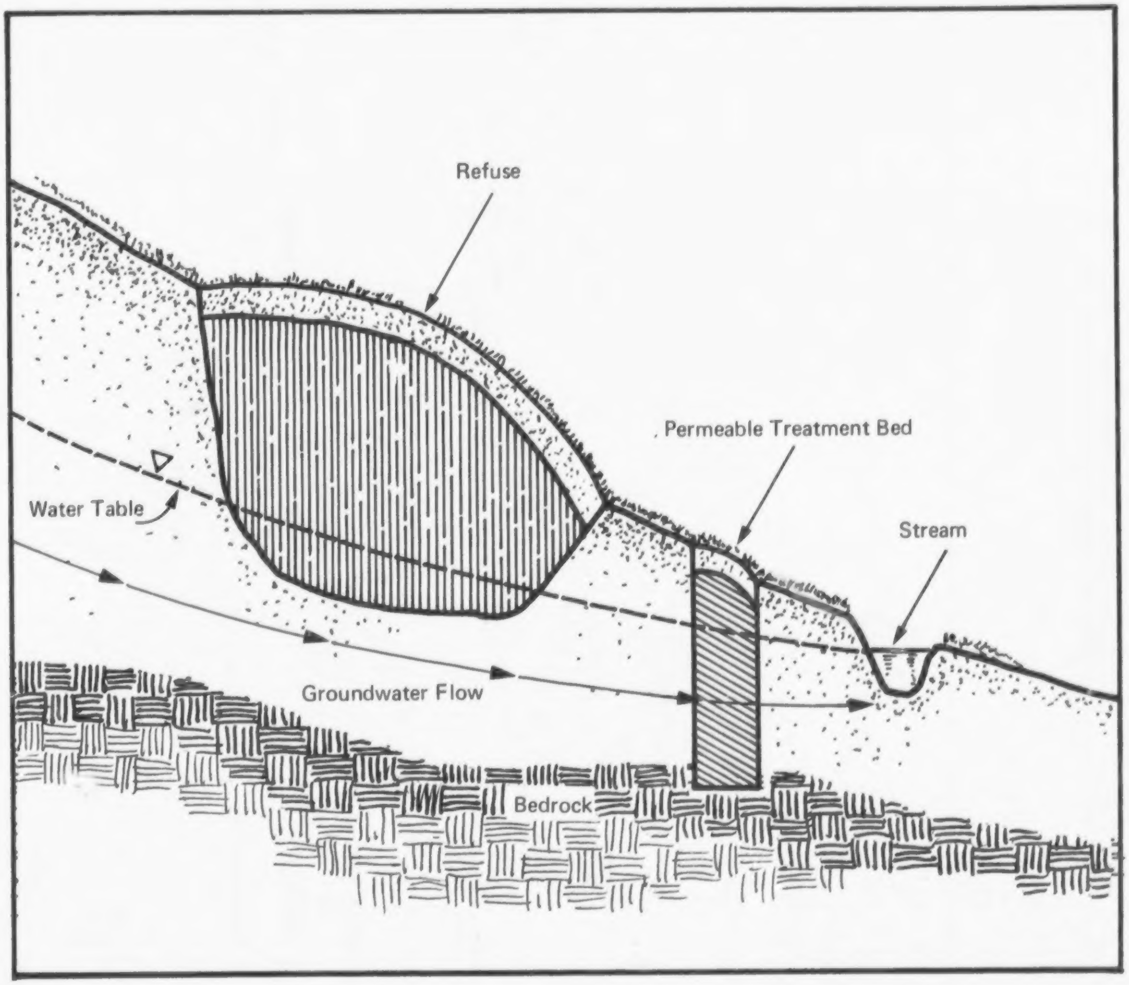
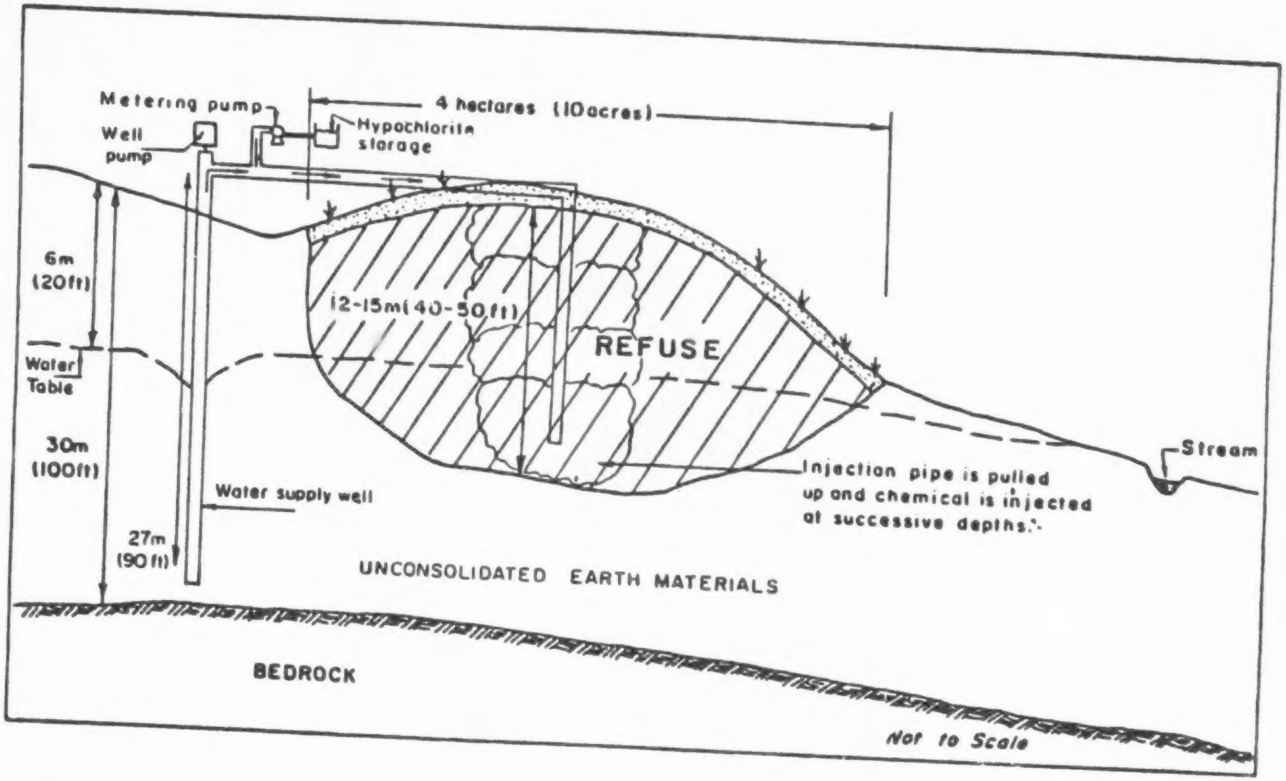

Refuse
Permeable Treatment Bed
Water Table
Stream
Groundwater Flow
Bedrock

FIGURE 4-32

CROSS SECTION OF LANDFILL TREATED BY CHEMICAL INJECTION

(Source: EPA, 1982)


Metering pump
Well pump
Hypochlorite storage
4 hectares (10acres)
6m (20ft)
Water Table
30m (100ft)
27m (90 ft)
Water supply well
12-15m(40-50ft)
REFUSE
Stream
Injection pipe is pulled up and chemical is injected at successive depths.
UNCONSOLIDATED EARTH MATERIALS
BEDROCK
Not to Scale

4.5.1.3 Feasibility and Effectiveness

General Features

Permeable treatment beds are applicable in relatively shallow aquifers since a trench must be constructed down to the level of the bedrock or an impermeable clay. Permeable treatment beds often are effective only for a short time as they lose reactive capacity or become plugged with solids. Over-design of the system or replacement of the permeable medium can lengthen the time period over which permeable treatment is effective.

The materials used for this form of treatment are:

- Limestone or crushed shell -- Limestone neutralizes acidic groundwater and may remove heavy metals such as Cd, Fe, and Cr. Dolomitic limestone (M_gCO_3) is less effective at removing heavy metals than calcium carbonate limestone. The particle size of the limestone should match a mix of gravel size and sand size. The larger sizes minimize settling of the bed and channeling as the limestone dissolves. The small sizes maximize contact. Extrapolated bench-scale data indicate contact time needed to change 1 pH unit is 8 to 15 days.
- Activated carbon -- Activated carbon removes non-polar organic contaminants such as CCl_4, PCBs, and benzene by adsorption. Activated carbon must be wetted and sieved prior to installation to ensure effective surface solution contact.
- Glauconitic green sand -- This sand, actually a clay, is found predominantly on the coastal plain of the Mid Atlantic states and has a good capacity for adsorbing heavy metals. Bench-scale studies indicate removal efficienccies of greater than 90 percent for As, Cu, Hg, and Ni, and 60-89 percent for Al, Cd, Ca, Cr Co, Fe, Mg, Mn and Zn, for detention times on the order of several days.
- Zeolites and synthetic ion exchange resins -- These materials are also effective in removing solubilized heavy metals. Disadvantages such as short lifetime, high costs, and regeneration difficulties make these materials economically unattractive for use in impermeable treatment beds.
- Chemical injection -- Sodium hypochlorite has been used to treat leachate containing cyanide (Colman et al., 1978).

Very little field data are available. The areal spread and depth of the leachate plume must be well characterized so that injection wells can be placed properly to intercept all of the contaminated groundwater.

Special Precautions and Limitations

Permeable Treatment Beds

- Plugging of the bed may divert contaminated groundwater and channeling through the bed may occur. Both problems permit passage of untreated wastes.
- Changing hydraulic loads and/or contaminant levels may render the detention inadequate to achieve the design removal level.

Injection

- Displacing pollutants to adjacent areas due to the added volume of chemical solution.
- Producing hazardous compounds by reaction of injected chemical solution with waste constituents other than the treatment target.

4.5.1.4 Design Basis

A permeable treatment bed is constructed by digging a trench to an impermeable layer (bedrock or clay), filling the trench with the appropriate material and capping to control infiltration. The width of the trench is determined by the permeabililty of the material used for treatment, the groundwater flow velocity and the contact time required for treatment. These parameters are related as:

$$w_b = (v_b)(t_c)$$

where:

w_b = barrier width (m)

v_b = groundwater flow velocity in the barrier (m/sec)

t_c = contact time to achieve the desired removal (sec)

Groundwater velocity in turn is determined by Darcy's Law:

$$v = ks$$

where:

s = the gradient or loss of head per unit length in the direction of flow (unitless)

k = coefficient of permeability, a soil-specific value (m/sec)

Since the groundwater velocity through the permeable bed cannot be predetermined, the trench should be designed for the maximum groundwater velocity through the soil. If one assumes the hydraulic gradient is equal for the soil and the permeable bed, the permeability of the barrier must equal that of the soil.

4.5.1.5 Principal Data Requirements

Plume characteristics (bed design)

- depth to bedrock
- plume cross-section
- leachate or groundwater velocity
- hydraulic gradient

Soil permeability - laboratory test (bed design)

Leachate composition (reaction medium selection)

Reaction rate - laboratory test (contact time)

4.5.1.6 Elements of Cost Review

Components

Construction and Capital--

Permeable Treatment Beds

- bed construction
- permeable medium
- monitoring instrumentation

Chemical Injection

- injection wells
- monitoring instrumentation

O & M--

Permeable Treatment Beds

- medium regeneration and/or replacement

Chemical Injection

- chemicals

Major Factors

Permeable Treatment Beds

- size of bed
- type of permeable medium

Chemical Injection

- number of injection wells

- type of chemicals

Data

Cost for in situ leachate treatment are site specific. Unit costs for potential detoxification chemicals are given in Table 4-35. A cost example for in situ detoxification is presented in Table 4-36.

4.5.2 In Situ Physical/Chemical Treatment

4.5.2.1 Description

In situ physical/chemical treatment involves the direct application of a reactive material to a surface impoundment or to landfilled waste to decontaminate the hazardous components. An example of physical treatment is the addition of activated carbon to adsorb organics. Chemical treatment involves neutralization, precipitation and/or oxidation-reduction reactions; reagents can be found in the appropriate leachate treatment section.

4.5.2.2 Status

Developmental. The basic physical/chemical methods to treat waste have been developed and applied to segregated industrial waste streams. In situ applications at uncontrolled sites have been limited.

4.5.2.3 Feasibility and Effectiveness

General Features

In situ physical/chemical treatment methods applicable to homogenous concentrations of specific waste types include (EPA, 1982):

- oxidation of cyanide waste with sodium hypochlorite;
- reduction of hexavalent chromium with ferrous sulfate;
- precipitation of heavy metals with alkali agents; and

TABLE 4-35
COSTS OF POTENTIAL IN-SITU NEUTRALIZATION/
DETOXIFICATION CHEMICALS

Chemical	1982 Unit Costs
Calcium Chloride, 100 lb bags	$160/ton
Calcium Sulfate	$36.20/ton
Potassium Permanganate	$2.02/kg
Hydrogen Peroxide, 50%	$0.28/lb
Sodium Hydroxide, liquid 50%	$250/ton
Ferrous Sulfate	$80/ton

Source: EPA, 1982

- adsorption of organics with activated carbon.

Special Precautions and Limitations

The waste to be treated should be physically isolated from waste which is not compatible with the treatment reagent. Heterogeneous wastes are not generally suitable for application of insitú treatment methods. For example, application of a hypochlorite solution to treat a cyanide waste constituent could chlorinate organic waste constituents to produce other hazardous materials.

4.5.2.4 Design Basis

Performance characteristics will be specific at each site application. An application of 15 percent hypochlorite solution to a 24 cubic meter pit of cyanide contaminated soils (100 ppm cyanide) yielded significant cyanide reductions based on groundwater monitoring data at the site (Kastman, 1977). Factors which affect engineering performance are:

TABLE 4-36
COSTS FOR IN-SITU DETOXIFICATION OF CYANIDE

Exploration probing, excavation, and drilling	$20,700
Development of water supply well, 27 m (90 ft); pump and piping	6,900
Installation of 45 well points	13,800
Cost of chemical feed pump	2,760
Cost of chemical (sodium hypochlorite)	6,900
Labor for chemical injection, raising of well points to flood successive elevations (assumed 4 wells handled simultaneously), and general labor (1,600 hours)	65,300
Power (assumed electrical supply available)	640
	$117,000

[a] Assumed 10-acre landfill with a total of 1,566 lbs of cyanide distributed within a fill volume of 4.9 million cubic feet. Chemical application rate of 68 gallons per pound of cyanide.

Source: EPA, 1982

- the ability to mix the waste and the detoxifying agent, i.e., stirrers for surface impoundments, cultivators for landfill;
- the homogeneity of the waste mixture; and
- the availability of the waste constituents to react with the detoxifying agent.

4.5.2.5 Principal Data Requirements

Site hydrogeology

Waste composition and distribution

Reaction rate (laboratory test)

4.5.2.6 Elements of Cost Review

Components

Construction and Capital--

- excavation
- well or trench installation
- monitoring instrumentation

O & M--

- chemicals

Major Factors

- type of chemicals
- area requiring treatment

Data

No information available.

4.5.3 On-Site Physical/Chemical Treatment

4.5.3.1 Description

The description of on-site physical/chemical treatment technologies can be found in the discussion of individual leachate control technologies.

4.5.3.2 Feasibility and Effectiveness

Physical/chemical methods could be applicable to aqueous waste mixtures recovered on site. For example, the contaminated water of a surface impoundment containing chlorinated cleaning solvents could be neutralized. In general, any on-site liquid waste could be considered amenable to physical/chemical leachate treatment methods if the waste characteristics fall into the concentration ranges applicable to leachate.

4.5.3.3 Elements of Cost Review

See sections on physical and chemical leachate treatment for costs of various unit operations.

4.5.4 In Situ Vitrification

4.5.4.1 Description

In situ vitrification is the melting of wastes and soil in place to bind the waste in a glassy, solid matrix. In one process (Battelle), wastes and soils are melted by passing an electric current through the material between the electrodes.

4.5.4.2 Status

Developmental. Battelle Pacific Northwest Laboratories is researching and developing an in situ vitrification process (Chemical Engineering, 1981).

4.5.4.3 Feasibility and Effectiveness

General Features

In situ vitrification has been sucessfully demonstrated in laboratory and pilot scale tests with soils contaminated with radioactive waste/soil mixtures. The process should be compatible with non-volatile, inorganic waste/soil mixtures in general.

Special Precautions and Limitations

If volatile compounds are present, off-gases may be generated.

4.5.4.4 Design Basis

- Power Consumption about 2000 kW/m^3 (Brown, 1982)
- Melting temperatures about 1700 °C

4.5.4.5 Principal Data Requirements

Composition and extent of waste/soil mixture (implementability)

Treatability tests (laboratory and field tests)

4.5.4.6 Elements of Cost Review

Components

Construction and Capital--

- electrodes
- generator
- air pollution control equipment
- monitoring instrumentation

O & M--

- electricity

Major Factors

- Volume of wastes

Data

No information available.

4.5.5 Solution Mining (Extraction)

4.5.5.1 Description

Solution mining (extraction) is the application of a solvent to a waste solid or sludge, and collection of the elutriate at well points for the removal and/or treatment of hazardous waste constituents. Typically, solvents used are water, acids (sulfuric, hydrochloric, nitric, phosphoric, carbonic), ammonia, and/or chelating agents such as EDTA (ethylene diamine tetra-acetic acid) which solubilize heavy metals and other inorganic ions. As the solvent is collected, a fraction can be recycled through the landfill with a make-up solution. The remainder can be treated and disposed of.

4.5.5.2 Status

Conventional, undemonstrated; chemical extraction has been used by the chemical processing and mining industries for many years. The techniques are well understood, but experience with in-situ treatment of hazardous waste is lacking. Bench-scale laboratory studies of extraction of heavy metals from sludges and plans to conduct full-scale metal extraction from industrial wastes have been made.

4.5.5.3 Feasibility and Effectiveness

General Features

Very little data are available on the application of this technology in a remedial action setting.

Special Precautions and Limitations

The design and placement of injection and withdrawal wells must prevent surrounding groundwater contamination with extracting solvents and extracted material.

4.5.5.4 Design Basis

- Selection of extraction solvent
- Well placement
- Injection location of extracting solvent

4.5.5.5 Principal Data Requirements

- Laboratory Testing

  Extraction efficiency of various solvents for solution mining of waste. Waste analysis for presence of constituents not compatible with solvent.

- Field Testing

  Geohydrologic site survey to establish potential for solvent migration into uncontaminated groundwater and to establish well placement sites for colleciton of elutriate.

4.5.5.6 Elements of Cost Review

Components

Construction and Capital--

- well construction
- monitoring instrumentation
- pumps

O & M--

- chemicals

Major Factors

- Volume of wastes

Data

Unit costs for eight potential extraction chemicals are given in Table 4-37.

4.5.6 Biodegradation

4.5.6.1 Description

If wastes are biodegradable, in situ treatment of the waste material using microorganisms may be a feasible treatment process. Many naturally occurring bacteria break down chemicals via metabolic activity (ingestion, respiration). Bacteria may be adapted from naturally-occurring bacteria to break down specific constituents in soil, and can be purchased in bulk quantity for that purpose. Most biodegradation processes used to treat hazardous wastes are aerobic; the technique usually used is to seed the waste material in situ with microorganisms or transport and spread the waste on aerated soils (land treatment). Surface impoundments in which the wastes may be mechanically aerated are also candidates for using in situ biodegradation.

4.5.6.2 Status

- Land treatment -- conventional, demonstrated at controlled sites, but application to remedial action at uncontrolled sites is uncertain.
- In situ biological seeding -- developmental.

4.5.6.3 Feasibility and Effectiveness

General Features

For in situ biological seeding, continuous seeding may be

TABLE 4-37
UNIT COSTS FOR EXTRACTION CHEMICALS

Chemical	1982 Unit Cost
Hydrochloric Acid, 20% acid	$ 85/ton
Nitric Acid, up to 42 Be	175/ton
Sulfuric Acid, Virgin	52.10-83.80/ton
Sulfuric Acid, Smelter	6-52.10/ton
Caustic Soda, Liquid 50%	250./ton
Citric Acid	0.04/1b
Sodium Lauryl Sulfate, 30%	0.22/1b

Source: EPA, 1982

required where there are other microbial predators, excessive washout, and/or other adverse environmental conditions such as presence of toxic metals.

Biodegradation has been used most widely for treatment of oily sludges and refinery waste. Bacteria developed for biological seeding are capable of degrading:

- benzenes
- phenols
- cresols
- naphthalenes
- gasolines
- kerosenes
- cyanides

Special Precautions and Limitations

In land treatment, if soils are not well aerated, waste degradation will not occur. Because metals are not degraded carful attention should be given to the toxic metal load at the site.

4.5.6.4 Design Basis

Key factors for biodegradation include:

- nutrient balance
- pH maintenance
- soil aeration
- degradation rate of wastes constituents

For detailed information on the design and management of land treatment facilities, see TRD 8.

4.5.6.5 Principal Data Requirements

Type, quantity, and distribution of waste constituents (seed, nutrient, air requirements)

site typography and hydrogeology (injection, withdrawal system design)

soil-physical, chemical, and biological properties (seed and nutrient requirements)

4.5.6.6 Elements of Cost Review

Components

Construction and Capital--

- spreading wastes
- aeration

O & M--

- analysis
- soil cultivation

Major Factors

Volume of waste

Data

Total biannual cost for in situ biological degradation of wastes on a one acre plot is $11,200 (1982 dollars).

4.5.7 Solidification/Stabilization

4.5.7.1 Description

Solidification/stabilization technologies (referred to as solidification technologies in this section) reduce leachate production potential by binding waste in a solid matrix by a physical and/or chemical process. Wastes are mixed with a binding agent and subsequently cured to a solid form.

4.5.7.2 Status

Cementation (including pozzolanic) -- conventional, demonstrated. Other processes -- developmental.

4.5.7.3 Feasibility and Effectiveness

General Features

Four approaches, identified in the literature, are:

- Cementation: Used to treat inorganic waste streams with Portland cement. This solidification technology is the least sensitive to waste variability.
- Pozzolanic cementation: Treats inorganic waste streams using what is often another solid waste (fly ash or cement kiln dust). The solidified product is more porous than the one using Portland cement.
- Thermoplastic binding: Treats wastes with binders such as bitumen, paraffin and polyethylene. These materials have been used on radioactive wastes, for which the technology was developed.
- Organic polymer binding: Treats wastes with polymer forming organic chemicals, such as urea and formaldehyde. This option was also developed as a disposal method for radioactive wastes. One organic polymer used is urea-formaldehyde.

Solidification technologies have been most successful when applied to inorganic waste streams. Wastes composed of 10-20 percent organic content are generally not amenable to solidification technologies (EPA, 1980). Exceptions are noted in the literature. For example, an oily sludge which was stabilized in a lime-treatment process (Soil Recovery, Inc., Morristown, NJ).

Abandoned sites with large volumes of contaminated soils, inorganic sludges, solids and/or concentrated inorganic aqueous wastes are prime candidates for application of solidification methods. To improve the homogeneity and suitability of wastes for solidification, waste could be blended with contaminated soil. The solidified product would be in a form suitable for on-site landfill or basic construction.

Special Precautions and Limitations

Treatable waste forms and waste classes that interfere with solidification are summarized in Table 4-38.

TABLE 4-38
SUMMARY OF TREATABLE WASTE FORMS AND INTERFERING WASTE CLASSES

Solidification Technology	Treatable Waste Forms	Interfering Waste Classes
Cementation (including Pozzolanic)	Waste slurries	Sulfate, Borates
Thermoplastic binding	Dried waste	Nitrates, Chlorates, Perchlorates, Organic Solvents
Organic polymer binding	Dewatered waste	Toxic metal salts

Source: TRD 6

Research is being conducted on long-term considerations such as product stability over the course of several freeze/thaw cycles.

4.5.7.4 Design Basis

Key design factors are:

- solidification mixing ratios;
- curing time; and
- volume increase of solidified product.

The evaluation of these factors is dependent on the solidification technology and the specific waste being treated.

4.5.7.5 Principal Data Requirements

Waste characteristics (binding agent selection):

- pH
- buffer capacity

- water content
- total organic carbon (TOC)
- inorganic and organic constituents

Treatability tests (cure time, mix):

- leachability
- strength

4.5.7.6 Elements of Cost Review

Components

Construction and Capital--

- tanks
- pumps
- mixers

O & M--

- chemicals
- analysis

Major Factors

- solidification option used
- volume of waste
- pretreatment requirements

Data

A cost example (unit and total costs) is presented in Table 4-39.

4.5.8 Incineration

4.5.8.1 Description

Incineration combusts or oxidizes organic material at very high temperatures. The end products of complete incineration are CO_2 H_2O, SO_2, NO_x, and HCL gases. Emission control equipment (scrubbers, electrostatic precipitators) for particulates, SO_2, NO_x and products of incomplete oxidation are needed to control emissions of regulated air pollutants.

Common types of incinerators most applicable to hazardous waste include:

- rotary kilns,
- multiple hearth,
- fluidized bed, and
- liquid injection.

4.5.8.2 Status

Conventional, demonstrated.

4.5.8.3 Feasibility and Effectiveness

General Features

The key features of incineration methods cited previously are summarized in Table 4-40.

TABLE 4-39
COSTS OF CHEMICAL FIXATION FOR A DISPOSAL SITE
(1982 dollars)

Basis:
- Stabilized waste materials are not releasing toxic levels of pollutants.
- Cost of obtaining fixation agents (e.g., fly ash) is free.
- Only top ½m of landfill is mixed with fixation agents.

	Total Unit $	
Capital Costs	Lower U.S.	Upper U.S.
Excavating and Grading, Waste (27,685 m^3)	42,310	50,750
Excavation and Grading, Soil (16,910 m^3)	18,380	21,440
Application of Stabilized Waste Material (33,218 m^3)	221,820	461,250
Capital Cost (subtotal)	282,510	533,440
Overhead Allowance (25 percent)	70,630	133,360
Contingency Allowance (35 percent)	98,880	186,700
Total Capital Cost	452,020	853,500
O&M Costs		
Monitoring		
Sample Collection 12 days/yr (96 hr/yr)	890	1,820
Analysis	9,220	9,220
- Primary & Secondary Parameters - 12 background/yr - 12 downgradient/yr 24 samples/yr		
Total O&M Costs	10,110	11,040
Average Capital Cost/m^3 stabilized waste	$13.60	$25.70
Average O&M Cost/m^3 stabilized waste	$ 0.30	$ 0.33

Source: SCS, 1981

TABLE 4-40
KEY FEATURES OF MAJOR TYPES OF INCINERATORS

Type	Process principle	Application	Combustion temp.	Residence time
Rotary kiln	Slowly rotating cylinder mounted at slight incline to horizontal. Tumbling action improves efficiency of combustion.	Most organic wastes; well suited for solids and sludges; liquids and gases.	810-1,640°C (1,500-3,000°F)	Several seconds to several hours
Multiple hearth	Solid feed slowly moves through vertically stacked hearths; gases and liquids fed through side ports and nozzles.	Most organic wastes, largely in sewage sludge; well suited for solids and sludges; also handles liquids and gases.	760-980°C (1,400-1,800°F)	Up to several hours
Liquid injection	Vertical or horizontal vessels; wastes atomized through nozzles to increase rate of vaporization.	Limited to pumpable liquids and slurries (750 SSU or less for proper atomization).	650-1,650°C (1,200-3,000°F)	0.1 to 1 second
Fluidized bed	Wastes are injected into a hot agitated bed of inert granular particles; heat is transferred between the bed material and the waste during combustion.	Most organic wastes; ideal for liquids, also handles solids and gases.	750-870°C (1,400-1,600°F)	Seconds for gases and liquids; longer for solids

Source: Ghassemi, et al., 1981

Special Precautions and Limitations

If an incineration system is not working properly, incomplete combustion products that may be toxic can be emitted to the atmosphere. If halogenated materials are present, then air pollution control will be necessary to prevent the emissions of inorganic acids to the atmosphere.

Residual ash is typically inorganic. Since it probably contains a high concentration of metals, it should be handled as a hazardous waste.

4.5.8.4 Design Basis (Ghassemi et al., 1981)

- Afterburner temperature of 1200 degrees C (2012 degrees F) required by Federal regulations.
- Two second dwell time in afterburner required by Federal regulations.
- Three percent excess oxygen required by Federal regulations.
- A scrubber to remove SO_2 and HCL from gas emissions if necessary.

4.5.8.5 Principal Data Requirements

Waste constituents and characteristics (suitability)

- moisture content
- volatile materials content
- ash content
- ash specific level, specific gravity or bulk density
- ash particle size range
- carbon hydrogen, oxygen, halide, sulfur, nitrogen, phosporus content

- waste specific gravity, viscosity, and melting point
- metal content
- thermogravimetric analysis
- suspended and dissolved solids
- reactive chemical groups
- flammability, stability, detonation
- environmental sensitivity
- toxicity

Process characterization (pilot test):

- residence time
- temperature
- destruction efficiences
- ash residue
- gaseous effluent

4.5.8.6 Elements of Cost Review

Components

Construction and Capital--

- incineration unit
- pollution control equipment

O & M--

- fuel
- monitoring

- maintenance
- ash disposal

Major Factors

Process size

Data

Unit cost for rotary kiln incineration and multiple hearth incineration are given in Table 4-41.

4.5.9 Thermal Oxidation Systems

4.5.9.1 Description

Thermal oxidation destroys hazardous components in a gas by combustion. The major combustion products are carbon dioxide and water.

4.5.9.2 Status

Conventional, demonstrated.

4.5.9.3 Feasibility and Effectiveness

General Features

Two principal types of oxidation systems are:

- Flaring -- A flare consists of an ignition chamber in which an ignitable gas is allowed to combust in a controlled air environment. A pilot burner is used to ignite the vent gases. Steam is added to smokeless flares to convert any unburned heavy hydrocarbons to carbon dioxide and hydrogen (EPA, 1982). Usually, smokeless flares are not required for treating vent gases in waste disposal sites since the

TABLE 4-41
UNIT COSTS OF WASTE DISPOSAL BY INCINERATION
(1982 dollars)

	Assumption	Cost
Rotary kiln incineration	Installed cost	$50-200/lb/hr
	Annual maintenance cost	5%-10% of installed cost
Multiple hearth incineration	Dry solids (sludge 15% moisture)	
	Installed cost	$42-374/lb/hr
	Operating cost	$3-38/ton
Multiple chamber incineration	Installed cost	$14-29/lb/hr
	Operating cost (includes capital cost)	$26-27/ton

Source: EPA, 1982, Draft Report (6/80)

gases do not normally contain any hydrocarbons that generate smoke during combustion.

- Afterburners -- Afterburners are incinerators for gases and vapors. Additional fuel is added to the waste gas stream to generate a high temperature after combustion. Incoming gas and vapors passing through the afterburner decompose at the high temperatures in the presence of oxygen, producing carbon dioxide, water and other combustion products. In some cases afterburners incorporate a catalyst to facilitate oxidation at lower temperatures.

Special Precautions and Limitations

Use of flares and/or afterburners should be generally restricted to those pollutants which will not produce undesirable oxidation products such as fluorides.

The changes in air flow rate and composition can interfere with thermal oxidation systems. The extreme conditions and condition variability should be considered when designing the system.

4.5.9.4 Design Basis

Flares

- Gas and/or vapors must be flammable. Heating value of gas or vapors should be greater than 100 BTU/ft^3 (Lund, 1971).
- Flow rate of gas and vapors is a key design factor.

Afterburners

- Should be employed only to treat gases that can be oxidized at temperatures of 870 degrees C or less with a retention time of about 0.5-1.0 seconds.
- In cases where the gas is relatively unstable, a catalytic afterburner may be used to lower oxidation temperatures (540-870 degrees C).

4.5.9.5 Principal Data Requirements

Gas and vapor volume vented (average and extremes)(system capacity)

Concentration of contaminants in gas (implementability, capacity)

Destruction efficiencies (bench or pilot tests)

4.5.9.6 Elements of Cost Review

Components

Construction and Capital--

- flare burners

- afterburners
- vent installation

O & M--

- fuel

Major Factors

- capacity of burner
- fuel requirements

Data

Installed costs for a flare system range from $2,250 to $4,500, 1982 dollars, for 20 to 670 cubic feet per minute gas flow (EPA, 1982).

Installed costs for afterburner systems range from $9 to $37 (1982 dollars) and annual operating costs range from $12 to $48 (1982 dollars) (EPA, 1982).

4.5.10 Carbon Adsorption For Air Emissions

4.5.10.1 Description

Carbon adsorption systems consist of a tank, drum, or other container that supports a bed of activated carbon. Contaminated gas flowing through the carbon bed is adsorbed on the carbon surface due to Van der Waals attraction and chemical bonding. The adsorbed gases can then be removed from the carbon by raising the temperature, often by use of steam. This regeneration process may be carried out on site, or the carbon can be removed and taken to an off-site regenerator.

4.5.10.2 Status

Conventional, demonstrated.

4.5.10.3 Feasibility and Effectiveness

General Features

In cases where small gas volumes and/or gas with low organic concentrations are being treated, it is generally cheaper to replace rather than regenerate the spent carbon. If very toxic chemicals such as dioxins are present, it may be best to use a non-regenerative system and dispose of the spent carbon since regenerated carbon has lower removal efficiencies. When treating large volume gas streams, regenerative systems are generally the more economic choice.

Retentivity is dependent on the type of substance being adsorbed, so operating times are expected to be different for various chemicals, all other factors being constant. Table 4-42 lists several organic compounds with their retentivity before and after regeneration.

Special Precautions and Limitations

The air emissions from carbon adsorption units should be monitored to insure the unit is functioning properly.

4.5.10.4 Design Basis

The maximum time period that a carbon bed can operate without a loss of efficiency, i.e., before the carbon must be replaced or regenerated, may be calculated by using the following equation (EPA, 1982):

$$t_{max} = \frac{SW}{MQC_v/RT}$$

where:

t = maximum time of affective use, sec

S = fractional retentivity of adsorbent, mass adsorbate/mass adsorbent

TABLE 4-42
RETENTIVITY FACTORS OF ORGANIC COMPOUNDS

Adsorbate	Approximate Retentivity Weight Fraction[a]	Retentivity After Regeneration[b]
Benzene	0.25	0.06
Carbon Tetrachloride	0.45	0.20
Gasoline	0.07	0.02
Methyl Alcohol	--	0.01
Isopropyl Alcohol	0.18	0.01
Ethyl acetate	0.20	0.05
Acetone	0.10	0.03
Acetic acid	0.30	0.03

[a] Weight of adsorbate per weight of carbon retained in dry air stream at 20°C.

[b] Regeneration with steam at 150° C for 1 hour.

Source: EPA, 1982

W = mass of adsorbent in the bed, Kg
M = molecular weight of adsorbate, kg/mol
Q = volumetric flowrate of total gas, l/sec
R = gas constant, .082 l-atm/mol K
T = temperature, K
C_v = volume fraction of vapor in total gas

4.5.10.5 Principal Data Requirements

Type and concentration of contaminant in the waste gas system (carbon usage)

The total amount of vented gas (volume, carbon usage)

Carbon adsorption efficiency (laboratory tests)

4.5.10.6 Elements of Cost Review

Components

Construction and Capital--

- pumps
- carbon
- monitoring instrumentation

O & M--

- carbon replacement

Major Factors

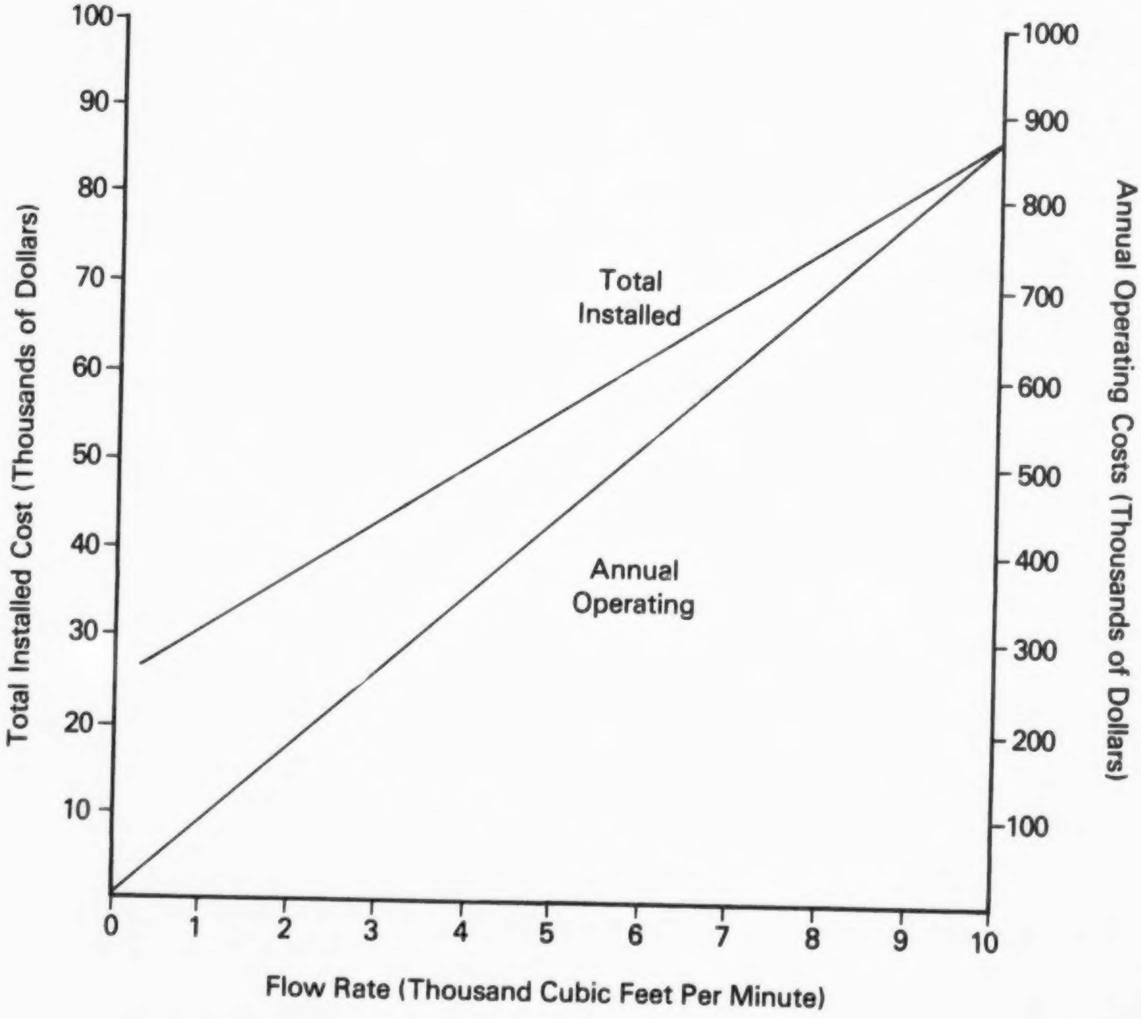
- air volume
- pollutant concentration

Data

A cost example is shown in Figure 4-33.

FIGURE 4-33

CAPITAL AND OPERATING COSTS FOR NON-REGENERATIVE CARBON ADSORPTION SYSTEMS TREATING VENT GAS CONTAINING 50 PPM TRICHLOROETHYLENE
(Source: EPA, 1982)



a. To update total installed costs to 1982 $, multiply by 1.12.
b. To update annual operating costs to 1982 $, multiply by 1.59.

SECTION 5

MONITORING TECHNIQUES

The principal objectives of monitoring systems at abandoned waste sites generally change over the life of a specific project. These objectives, in more or less chronological order, are:

- determination of exposure and contamination effects on humans, sensitive and important nonhuman species, and the environment.
- site assessment pursuant to design of a remedial action program.
- evaluation of the effectiveness of the remedial action program.

Any monitoring program must be designed with a clear focus on meeting one or more of these objectives. Failure to define objectives will generally result in less than optimal use of monitoring funds.

There are essentially two types of information that a monitoring program may be expected to provide:

- the setting (geologic, hydrologic, topographic, etc.) of the site, and
- the contamination distribution (type and concentration) at the site.

This information should elucidate the nature of the problem in the principal environmental media involved. These media, using the same categories as in Chapter 2, are:

- groundwater
- surface water
- soil
- air

Data on biota may also be required.

The major issues to be addressed in designing and conducting a monitoring program are:

- what methods to use;
- where (location) and when (frequency) information/samples will be collected;
- and how to analyze the samples.

The discussion below emphasizes the choice and location issues. Questions of frequency and laboratory analysis of samples taken at the site are only briefly examined.

Monitoring program design will vary depending on the objectives as indicated in Table 5-1. A monitoring program designed for site assessment prior to design of a remedial action program must lead to a characterization of the setting of the site as well as the levels and pattern of site-related contamination. The location of soil borings, monitoring wells, air samplers, etc. must provide a fairly detailed characterization of the physical environmental setting of the site (e.g., the characterization of subsurface soil profiles).

A monitoring program designed to evaluate the effectiveness of a remedial action would not normally require additional monitoring to characterize geology, but may demand "before and after" water or air flow characterization as well as contamination monitoring. The siting of monitoring devices will be focussed on the action (e.g., immediately downgradient of a cutoff wall, or immediately above a landfill "cap").

When monitoring is designed to assess exposure to human or non-human receptors, only contamination levels need to be monitored. Sampling locations siting should reflect locations of intensive use

TABLE 5-1
MONITORING PROGRAM DESIGN CONSIDERATIONS

Objective	Environmental Setting		Contamination	Comments	
	Geology/Topography	Flow (air or water)			
Exposure/Health Effects			X	Where	Consider all media; location is area of intensive use by human or sensitive and important non-human species.
				When	Dependent on exposure/health effect scenario.
Site Assessment	X	X	X	Where	Consider all media; location determined entirely by site setting characteristics.
				When	Depending on urgency, perhaps only one sample will be taken at each sampling location.
Evaluate Effect of Remedial Action		X	X	Where	Consider all media; locate so as to observe earliest effect (probably close to site of Remedial Action.)
				When	Dependent on nature of Remedial Action.

for the target organism (e.g., a marsh, bathing beach, or domestic well).

The remainder of this section consists of a discussion of general guidelines for designing monitoring programs (what, where, when) in order to meet the objective, followed by a brief summary of technologies and procedures for monitoring the setting of disposal sites and related contamination levels. In addition, monitoring wells are discussed in detail at the end of the section in the format of the technology discussions in Sections 3 and 4.

5.1 MONITORING PROGRAM GUIDELINES FOR REMEDIAL ACTION ASSESSMENT

The focus of this document and the following discussion is on the second of the three objectives listed above. Site assessment pursuant to design of a remedial program requires a comprehensive monitoring program in contrast to programs that might be developed to meet the other two objectives. Site assessment monitoring is intended to:

- define the setting in the soil phase (geology/topography) and in the air and water.
- determine the site-related contaminant distribution.
- determine rates of contaminant migration from the site.

To accomplish these objectives, decisions as to when, where, and what to monitor should be made based on the answers to the following questions:

- Where was the waste disposed?
- When was the waste disposed?
- What wastes are likely to be found at the site?
- What are likely to be important pathways for contaminant migration (air, surface runoff, groundwater)?
- In what direction would contamination likely migrate by each important pathway?
- How rapidly would it be likely to migrate?

- Given the period since the waste was disposed, how far is it likely to have traveled?
- Are there other sources of contamination in the vicinity?
- Are there other man-induced phenomena which may now, or during the site's lifetime, affect contaminant migration (for example, a major production well)?

The following approaches, by themselves, will not, in general, contribute to the remedial action plan assessment objective:

- sampling near property or political boundaries
- sampling on a predefined grid without regard to geologic or topographic consideration
- sampling a domestic well (unless it is fortuitously sited in a region of probable impact)
- sampling near a distant residential area
- sampling and analysis designed to monitor a predetermined list of contaminants (i.e., drinking water standards) without regard to wastes disposed at the site.

From archived information and a visual inspection of the site, possibly augmented by remote sensing procedures such as an electrical resistivity survey, a qualified hydrogeologist should be able to hypothesize in broad outline the direction of surface and shallow groundwater flow from the site as well as rough estimates of hydraulic gradient and permeability of the soils. This kind of procedure can generally give only an order of magnitude estimate at best. Applying Darcy's Law using the estimated characteristics, the downgradient extent of contaminated groundwater can be approximated. This estimation technique is general and is useful only in planning the monitoring program -- not for hazard assessment.

The results, however, may be extremely useful if they indicate that the contaminant should not have migrated far from the original waste location. In this case, monitoring wells need be sited only near the site with several downgradient and one or more upgradient. The number of monitoring wells to use is site-specific, depending not only on the complexity of the site, but to some extent on the perceived degree of hazard.

If there is evidence of significant downgradient contaminant migration, a more extensive pattern of monitoring wells may be recommended -- perhaps an inner semi-circle near the site to define the rate and quality of leachate migration, and outer rings or lines of wells downgradient to establish the full extent of contamination, as shown in Figure 5-1. The well pattern shown is designed to determine the extent of contamination.

The above techniques for defining the contamination is not necessarily the best way to define the flow regime. Definition of the flow regime may require additional piezometers and/or soil borings.

5.2 MONITORING FOR REMEDIAL ACTION EFFECTIVENESS

To evaluate the effectiveness of a remedial action program, monitoring needs will be defined from the type and location of the remedial actions. Monitoring systems should be designed to detect the effect of the remedial action as soon as possible after its construction. This need is usually met by two design criteria:

- measure the quantity/parameter directly affected by the action
- measure that quantity as close to the site of the action as practicable.

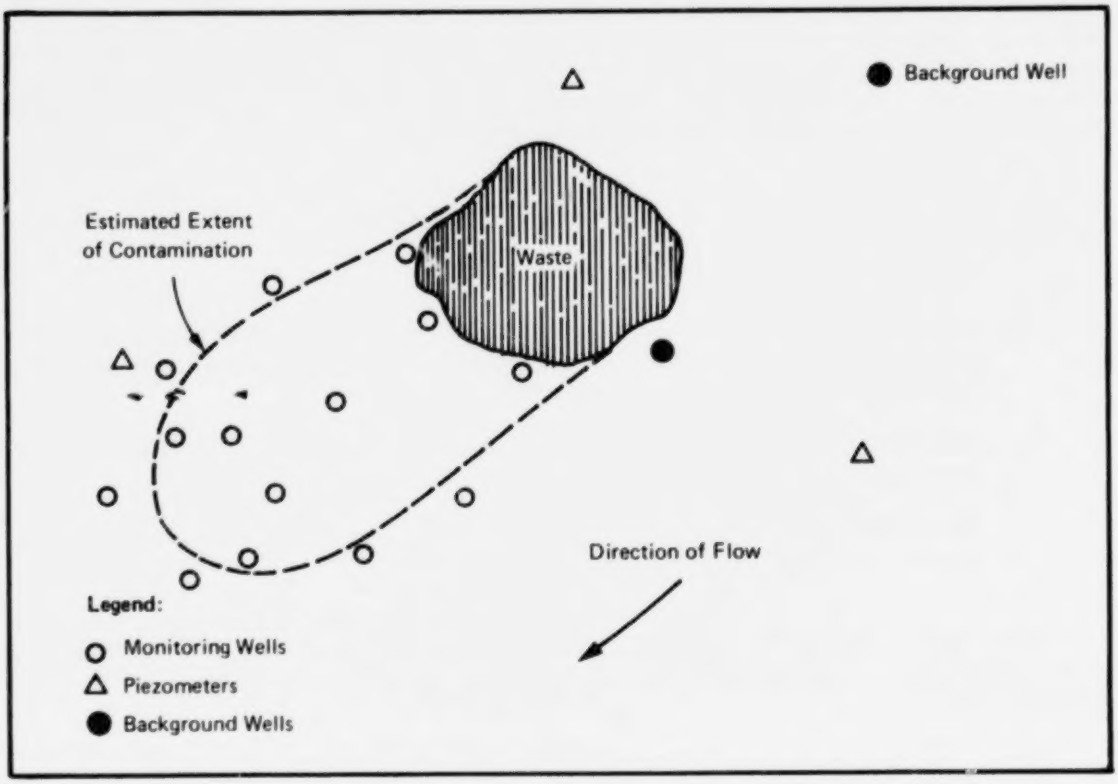
For example, if a capping program is designed to reduce volatile air emissions of organics, an air sampler should be situated near the ground over the capped area. Before and after sampling would normally be advisable.

As another example, if an extraction well were designed to lower the water table, one should install piezometers in the expected zone of influence. Taking groundwater samples for analysis may not be required to evaluate such a system. If, on the other hand, the intent of an extraction well is to reverse and collect the flow of a contaminated groundwater plume, monitoring wells should be installed near the leading edge of the plume.

Finally, in monitoring for health effects and toxic exposure, the best technique may be tissue samples from exposed people or other target species. Sampling of domestic wells in an area of possible contamination may be appropriate, as well as sampling air quality in a nearby residential area.

FIGURE 5-1

PLACEMENT OF MONITORING WELLS


Background Well
Estimated Extent of Contamination
Waste
Direction of Flow
Legend:
○ Monitoring Wells
△ Piezometers
● Background Wells

5.3 MONITORING AND SAMPLING TECHNIQUES

5.3.1 Monitoring and Procedures to Determine the Setting

The setting consists of:

- land characteristic -- geology, topography
- air and water characteristics -- winds, surface water levels and currents, groundwater heads and flow rates

At most sites a considerable base of information on the setting is available in existing data archives maintained by the United States Geological Survey (USGS), National Climatic Center of the National Oceanic and Atmospheric Administration (NOAA/NCC), U.S. Army Corps of Engineers, U.S. EPA, and state and local agencies. The available data may obviate the need for extensive data gathering. Usually, however, data from the conventional sources listed below are not locally detailed and sufficiently site-specific to support design of a remedial action plan. The most important readily-available data and their sources are:

- surface weather observations (NOAA/NCC)
- surface topography (USGS)
- surface water levels and discharge rates (USGS, U.S. Army Corps of Engineers, U.S. EPA, state and local water surveys and local water supply agencies)
- subsurface geology (USGS, state and local geological survey agencies)
- groundwater levels, yields, and discharge rates (USGS, state and local geological agencies)

The data sources above must generally be supplemented in site-specific assessment of waste sites in the following categories:

- surface water levels and discharge rates of minor streams are not generally available in archives -- techniques include staff gages (calibrated sticks or rules used to measure water level) and weirs;
- localized subsurface geology must be determined via soil borings and/or in situ well logging; and
- localized groundwater conditions must be determined via wells and/or piezometers.

Several well logging and in situ techniques may be useful in assessing local subsurface geology and subsurface moisture. Neutron moderation and gamma-ray attenuation are examples of two in situ techniques for determining moisture content. They are principally useful in the unsaturated zone, do not require sample collection, and provide "real-time" data useful in deciding where to collect a sample, screen a well, install a lysimeter, and so on.

Geophysical well logging provides indirect evidence of subsurface formation and relative permeabilities. Natural gamma radiation from subsurface materials indicates the presence of clay or shale. Electric resistivity logging records the apparent resistivity of subsurface formations, which will vary with particle size and the conductivity of the occluded water. Leachate is usually identifiable by its high conductivity, relative to natural, non-saline groundwater. These two procedures should generally be used in conjunction with each other in order to obtain a meaningful interpretation of the results. Figure 5-2 shows how a leachate plume may be detected via these techniques (Fenn et al., 1977).

5.3.2 Monitoring Procedures for Assessment of Site-Related Contamination

Most monitoring procedures described here are, essentially, sampling procedures. Standard procedures for analyzing water or other environmental samples are not addressed in detail. However, there is an important group of in situ tests which can determine contaminant distribution without collecting a sample, some of that can provide "real-time" diagnosis. The discussion of contamination assessment procedures is organized into the following categories: saturated groundwater, unsaturated soil zone, surface water, soil, biota, air, and remote sensing.

5.3.2.1 Saturated Groundwater Zone

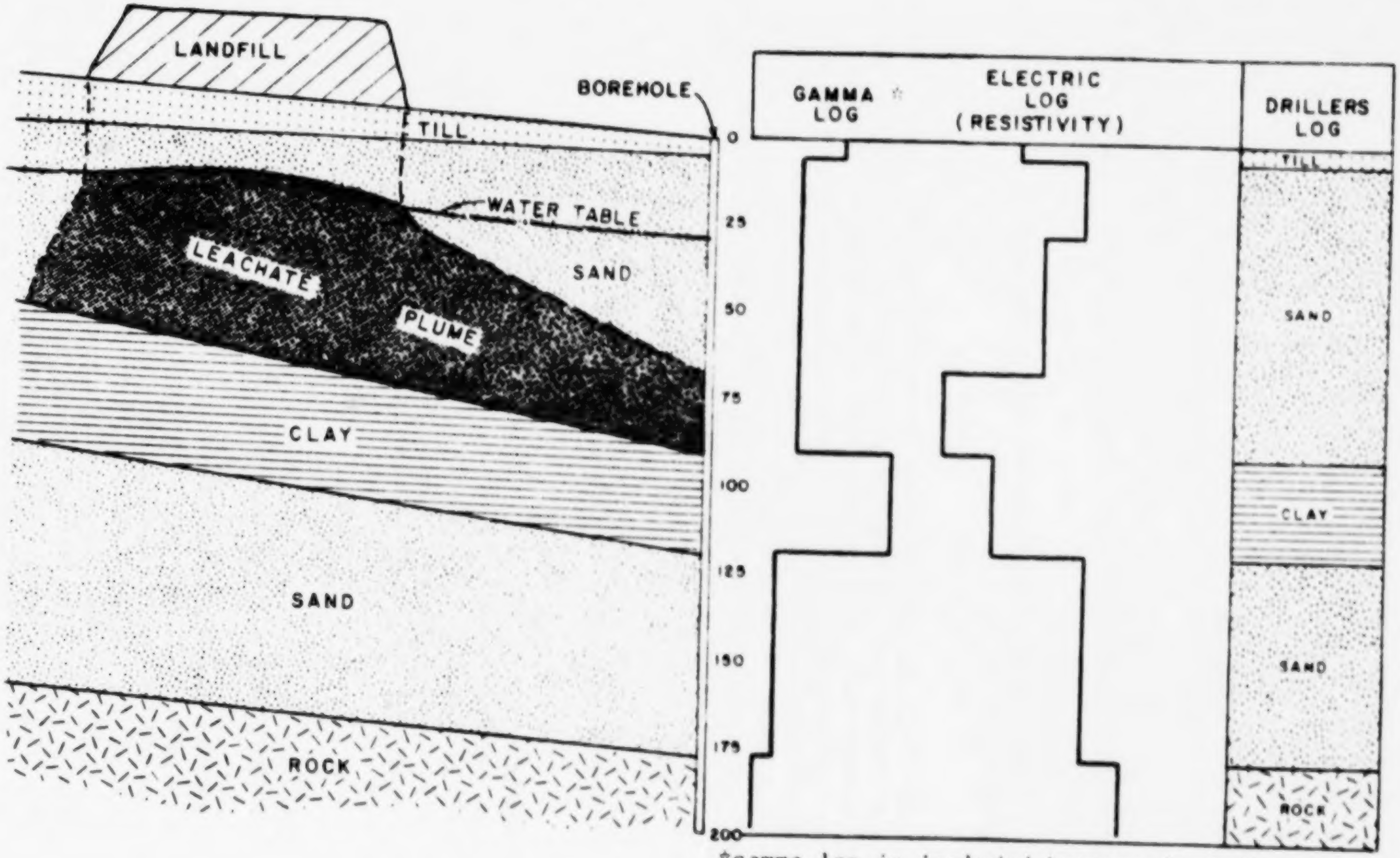
Groundwater from the saturated zone must generally be obtained from wells, though sampling of springs and leachate seeps may provide a fortuitous and inexpensive indicator of groundwater quality at some sites. Important considerations in developing wells for sampling groundwater near hazardous waste sites for subsequent analysis are:

- proper sealing to prevent the well itself from contributing to vertical migration of contaminants;
- special casing materials to prevent inadvertent sample contamination: PVC pipe is good for subsequent metals analysis while galvanized steel is good for subsequent organic analysis; other contaminant resistant materials include Teflon^R, fiberglass-reinforced epoxy pipes, stainless steel, and rubber-modified polystyrene (Everett, 1976); PVC with screwed (not glued) connections may also be used for some organic sampling.

FIGURE 5-2

DETECTION OF A LEACHATE PLUME USING AN ELECTRIC WELL LOG

(Source: Fenn, et al., 1977)


LANDFILL
TILL
WATER TABLE
BOREHOLE
SAND
LEACHATE
PLUME
CLAY
SAND
ROCK
0
25
50
75
100
125
150
175
200
GAMMA LOG *
ELECTRIC LOG (RESISTIVITY)
DRILLERS LOG
TILL
SAND
CLAY
SAND
ROCK

*gamma log is included because it indicates that the leachate plume is not actually a clay layer.

- drilling techniques and use of drilling muds which can affect in situ permeability tests and cause contamination of samples;
- well screen length and depth must be carefully selected to sample specific strata of the aquifer;
- sturdy well covers and anchoring with grout and/or cement to prevent contamination from the surface and discourage vandalism or inadvertent damage from other activities at the site; and
- procedures for protecting drilling teams and the general public if it is expected that toxic gases may be released during drilling.

Samples of groundwater are generally taken during well drilling. These samples may be very useful in deciding the appropriate screen depth to sample the most contaminated layer of the aquifer. Soil samples, commonly taken via split spoon or Shelby tube samplers, may be examined for qualitative evidence of contamination (with care to avoid toxic exposure).

Water sampling techniques during drilling include:

- drilling a casing or well point to a desired depth, bailing or pumping a sample and repeating the process to the completion depth;
- drilling a mud rotary boring, constructing a temporary well screen and packing, and pumping a formation water sample; and
- drilling a borehole to a desired depth, setting a packer pump and riser pipe and pumping a sample.

Procedures for obtaining soil samples during drilling are briefly discussed below. Soil pore water may be extracted from soils by filter press or centrifuge for subsequent analysis. Such procedures find greatest applicability in the unsaturated zone where it is more difficult to obtain a water sample.

5.3.2.2 Groundwater in the Unsaturated Zone

Lysimeters are the most common sampling devices for obtaining water from the unsaturated zone. Squeezing pore water from soil samples is the only practical alternative. Lysimeter designs include:

- vacuum
- trench

Vacuum lysimeters draw water through a porous ceramic cup emplaced in the soil, while trench lysimeters passively intercept percolating water. Thus, trench lysimeters are only effective when and where substantial percolation occurs, for example:

- under a hazardous waste lagoon, and
- immediately during and after rainstorms on a landfill.

Vacuum lysimeters are expected to find more general applicability at hazardous waste sites. However, pumping with vacuum is not generally used when volatile organics are suspected, as the vacuum pulls the volatiles out of solution.

5.3.2.3 Surface Water

Surface water sampling is a mature and relatively simple technology with well-standardized methods. Surface runoff collection may require small structures such as weirs to collect an adequate sample volume for analysis. Runoff may be collected also via soil plugs (screened cups which are driven into the soil so as not to alter the runoff flow).

5.3.2.4 Soil

Soil samples may be obtained from the saturated or unsaturated zone or as surface water-body bottom sediment. The solid phase may be extracted with chemical solvents to identify contamination adsorbed on or precipitated with the soil. Although extraction of soils may be performed on saturated soils, such procedures find greatest applicability in the unsaturated zone where it is more difficult to obtain a water sample. The technique has several disadvantages including:

- few labs are equipped for such analysis;
- there is no standard method;
- precise quantitative analysis of sorbed organics has not been adequately demonstrated to date; and
- analytical costs are higher than a simple water sample.

However, the technique does permit pinpointing of contaminated zones to a degree of spatial resolution not possible with well sampling where water is drawn from relatively larger volumes. Extraction may be the only feasible method for contamination assessment in unsaturated soils with low moisture content.

Remote sensing monitoring is used to provide a reasonably accurate assessment of subsurface contamination including the location and extent of buried wastes. The types of remote sensing techniques include:

Electrical Resistivity

- Resistivity is used to define a leachate plume based on the fact that leachate is more conductive than uncontaminated groundwater.
- Lateral profiling can be used to determine the areal extent of contamination and can assist in the placement of monitoring wells.
- Depth profiling indicates the change in contamination with depth and defines complex stratigraphy.

Ground Penetrating Radar

- Used to locate buried objects and to provide qualitative information about drum density, to detect interfaces between disturbed and undisturbed soil, and to detect leachate plumes.
- Based on the principle that electromagnetic pulses, reflected from subsurface interfaces or objects, are detected by antennae held at the ground.

Seismic Refraction

- used to locate interface between subsurface deposits and determine the nature of each deposit
- based on the principle that induced compression waves reflect at interfaces and refract depending on the properties of the new medium of propagation.

Fisher M-Scope and Proton Magnetometer -- used to detect buried metal objects.

5.3.2.5 Biota

Sampling and analysis of biota may, in some circumstances, provide an early indication of environmental quality deterioration for bioaccumulated contaminants whose concentration in ambient air or water is below detection limits. Another promising mode of investigation is the potential for visual assessment of vegetation stressed by contaminants. There are many advantages to bio-monitoring:

- provides the first indication of contaminant migration;
- can be used to locate contaminant plumes for direct sampling; and
- can be accomplished in a few hours on site by a trained ecologist.

However, the lack of visual stress does not necessarily imply a lack of contamination so the method is not foolproof.

5.3.2.6 Air Monitoring

Two types of air emissions can occur at waste sites, vaporization of volatile organic compounds and entrainment of particulate matter. Each type requires different monitoring procedures to measure the impacts. The following describes the steps to be taken to monitor the air quality impacts from a waste site.

Vaporization of Organic Compounds

- Collect vapors directly above or downwind of the site in sorbent traps or low temperature traps;

- Analyze the trapped vapors in laboratory gas chromatographs and mass spectrometers; and
- Relate concentrations to the ambient conditions by recording flow rates through the traps.

Entrainment of Particulate Matter

- Collect samples directly above or downwind of the site in hi-vol filter devices for approximately a 24-hour period;
- Weigh the filters to determine total suspended matter collected;
- Analyze the filters by optical and electron microscopy and by X-ray fluorescence to identify species collected; and
- Relate collected mass of each species to ambient concentrations by considering air flow rates through the filter.

5.3.3 Monitoring Wells

5.3.3.1 Description

There are four major types of wells used for groundwater monitoring:

- single screen wells, which sample a single vertical interval;
- multiple screen wells, which sample more than one vertical interval;
- well clusters, or a set of single wells placed closely together, which sample more than one vertical interval; and
- piezometers, which measure the hydrostatic pressure of the water table.

These are shown in Figures 5-3 through 5-6.

FIGURE 5-3

SINGLE-SCREENED WELL
(Source: Fenn, et al., 1977)

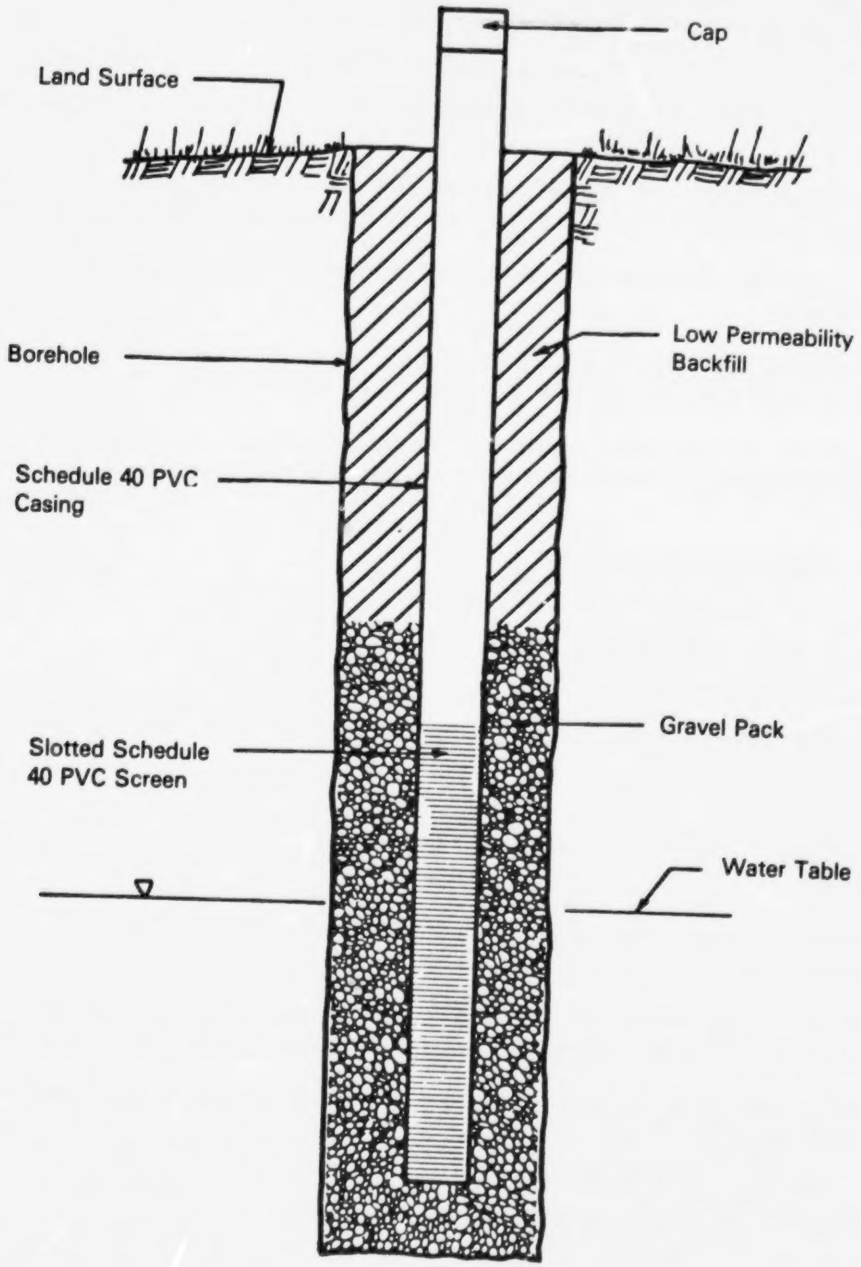

Cap
Land Surface
Borehole
Low Permeability Backfill
Schedule 40 PVC Casing
Gravel Pack
Slotted Schedule 40 PVC Screen
Water Table

FIGURE 5-4

MULTIPLE-SCREENED WELL PUMP
(Source: Fenn, et al., 1977)

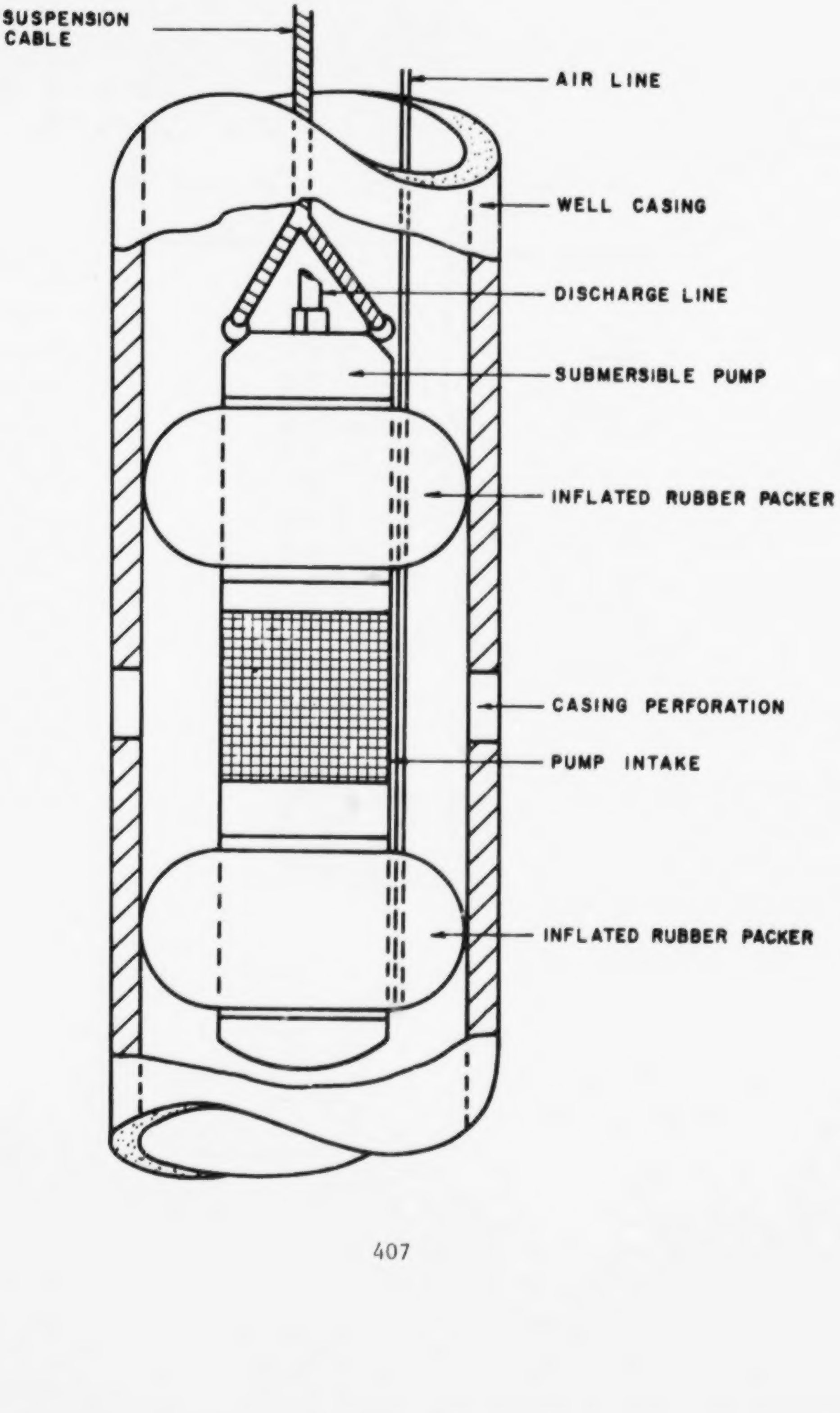

SUSPENSION CABLE
AIR LINE
WELL CASING
DISCHARGE LINE
SUBMERSIBLE PUMP
INFLATED RUBBER PACKER
CASING PERFORATION
PUMP INTAKE
INFLATED RUBBER PACKER

FIGURE 5-5

WELL CLUSTER
(Source: Fenn, et al., 1977)

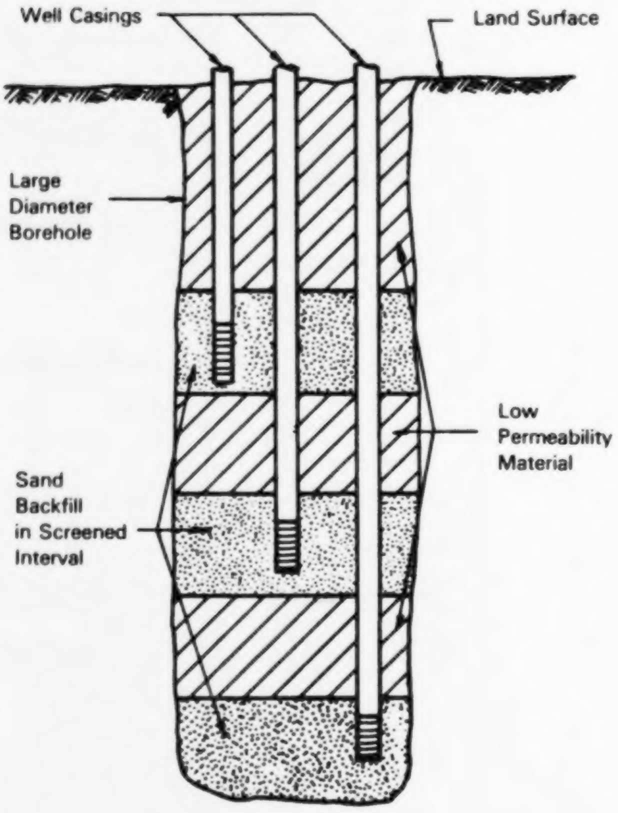
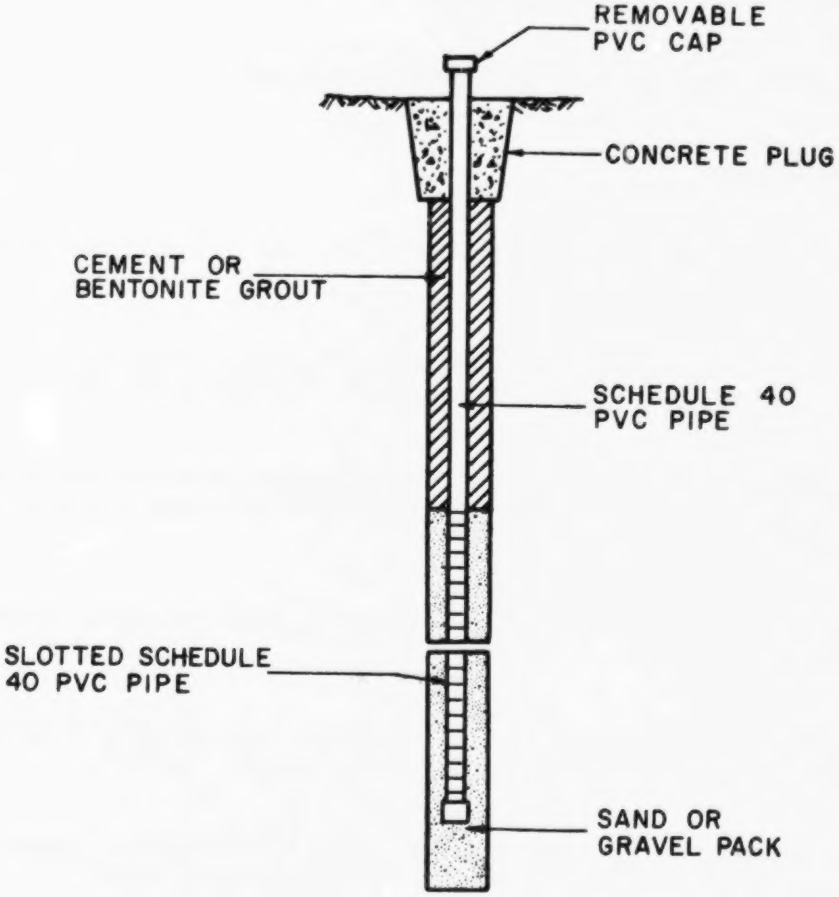

Well Casings
Land Surface
Large Diameter Borehole
Low Permeability Material
Sand Backfill in Screened Interval

FIGURE 5-6

PIEZOMETER WELL
(Source: Fenn, et al., 1977)


REMOVABLE PVC CAP
CONCRETE PLUG
CEMENT OR BENTONITE GROUT
SCHEDULE 40 PVC PIPE
SLOTTED SCHEDULE 40 PVC PIPE
SAND OR GRAVEL PACK

Monitoring wells, properly placed, can be used to characterize the vertical and horizontal extent of groundwater contamination.

5.3.3.2 Status

Conventional, demonstrated. Well clusters have been the most common and successful technique for delineating groundwater contamination. (Fenn et al., 1977)

5.3.3.3 Feasibility and Effectiveness

Well Types

Single-Screen wells-- Useful in two situations (Fenn et al, 1977):

- to obtain composite groundwater samples when screened (or open) over the entire saturated thickness of the aquifer; and
- to sample deep aquifers when the major part of the sampling program is aimed at the zone of aeration and the top of the saturated zone.

They are not effective for determining the vertical distribution of contamination.

Multiple-Screen wells-- Effective for determining vertical distribution of contamination if (Fenn et al., 1977):

- the packer pump and annular seal effectively isolate the pumped portion from the rest of the aquifer; and
- pumping rates are kept low and pumping is not prolonged so that water is drawn only from opposite the screened section.

Well-clusters-- The most common and successful technique for determining vertical distribution of contamination. Well clusters are not 100% effective, however, as portions of the vertical area remain unsampled.

If well clusters are constructed in a single, large-diameter bore hole, the seals between individual wells must be carefully constructed and precautionary measures taken, such as using a shrinkage-inhibitor in the grout. (Fenn et al., 1977)

Piezometers-- Must have an impermeable seal in the annular space above the screen (Fenn et al., 1977). Therefore, any single-screen monitoring well that meets RCRA requirements may also be used as a piezometer.

Well Placement

No specific rules for the placement of monitoring wells are possible. Wells should be placed both upgradient and downgradient of the site at strategic points in the aquifer(s) and throughout its entire vertical depth.

In the simplest case, a single aquifer with uniform flow, a minimum of four wells are required to determine the direction of flow and the hydraulic gradient. Three wells are used to determine the plane of groundwater flow. A fourth, placed in the line of flow from one of the other three, is then used to determine hydraulic gradient. More wells are required for more complex aquifer systems.

Well placement depends on:

- depth to water table;
- direction of groundwater flow;
- hydraulic conductivity;
- effective porosity;
- hydraulic gradient;
- soil compaction;
- soil strength properties;
- leachate characteristics;
- economic considerations; and
- other site-specific considerations.

Well Construction

Drilling techniques-- A list of techniques with maximum drilling depth and typical well diameter is given in Table 5-2.

Drilling techniques, especially types of drilling mud used, should be carefully selected so as not to interfere with sampling. Selection of drilling technique will depend on:

- rock type;
- soil compaction;
- diameter and depth of well;
- site accessibility;
- availability of drilling water; and
- economic considerations.

Casing-- In general casing material should be:

- plastic if metal analysis is important. If depth < 16m (52 ft), use schedule 40 PVC, and if depth > 16m, use schedule 80 PVC (Absalon and Starr, 1980);
- steel if hydrocarbon analysis is important. (Mooij and Rovers, 1976); and
- steel or wrought iron if considerable strength is required during installation. (Walton, 1970).

Selection of casing material depends on

- parameters to be sampled;
- drilling technique;
- depth of well;
- leachate characteristics; and
- groundwater quality (corrosive or encrusting).

TABLE 5-2
DRILLING TECHNIQUES

Technique	Max. Depth (m)	Typical Well Diameter	Comments
Dug	13 (40ft)	2.5m (8ft)	Generally not applicable for monitoring
Augered			
Hand	6.5 (20)	5-10cm (2-34 in.)	For unconsolidated materials
Power	65 (200)	5-90cm (2-32in.)	For unconsolidated materials
Driven	10 (30)	4-11cm (1.5-4in.)	For unconsolidated materials
Jetted	50 (150)	5cm (2in.)	Best in sandy soils
Drilled			
Cable tooled	100 (300-small rig) 2300 (7000-large rig)	14-65cm (5-24in.)	Good for sampling and logging
Rotary	-	16-22cm (6-8in.)	Good for consolidated materials

Source: Everett et al, 1976

Diameter

A 5 cm (2 in.) inside casing diameter is most common. Typical range for monitoring wells is 3 - 16cm (1.25 - 6 in.). (Mooij and Rovers, 1976.)

Screen

The choice of screen materials depends on the type of casing. Plastic casing can be slotted in the field and covered with fiberglass cloth or encased with a sand or gravel pack. A sand or gravel pack is appropriate in consolidated soils or in unconsolidated soils with a permeability less than 10 - 2cm/sec. It should extend 16 - 32 cm (6 - 12 in) above and below the slotted area. Manufactured steel screens are used for steel casings. Galvanized steel may affect water quality analysis (Mooij and Rovers, 1976). Selection of screen material depends on:

- parameters to be sampled;
- drilling technique;
- depth of well;
- leachate characteristics; and
- groundwater quality (corrosive or encrusting).

Slot size (the size of the screen opening) depends on the grain size distribution, grading, and the structural integrity of the aquifer material. Recommended slot sizes, based on the percentage of aquifer material that should not pass through the screen, are given in Table 5-3.

The screen should extend over entire vertical span of interest.

Annular Space

The annular space above (or between) sampling depths should be sealed with impermeable material (such as cement grout or bentonite slurry) to prevent contamination of samples with water from contaminating other aquifers. This is a requirement for monitoring wells under RCRA.

TABLE 5-3
SLOT SIZE

Aquifer Material	Cave-in Potential	Slot Size (%of aquifer material retained)
Artificial (sand or gravel) pack	--	90
Natural pack		
Poorly graded	No	30
Poorly graded	Yes	50
Well graded	No	40
Well graded	Yes	60

Source: Walton, 1970

Well Development

Wells should be developed (pumped out) before sampling and, again, periodically during sampling to remove silt, fine sand, and other materials from the zone immediately around the well. (Everett, et al., 1976.) Pumping should continue until measurements of conductivity, chlorine, and hardness are consistent. In highly permeable soils a minimum pumping volume of five well casing volumes is recommended. In relatively impermeable soils wells should be pumped dry and the incoming water analyzed. This process is repeated until the above parameters are constant (Mooij and Rovers, 1976).

Special Precautions and Limitations

Drilling techniques, construction material and well design should be carefully selected so as not to interfere with sampling.

5.3.3.4 Principal Data Requirements

The principal data considerations for monitoring wells are summarized in Table 5-4.

5.3.3.5 Elements of Cost Review

Components

Construction and Capital--

- well drilling
- pumps
- casing and screening material
- sealant for annular space

O & M--

- electricity for pump
- pump maintenance
- sample collection and analysis

Major Factors

- number and depth of wells
- casing and screening material
- pump size
- drilling technique
- sample analysis required

Data

Cost information for various types of monitoring wells are given in Table 5-5.

TABLE 5-4
PRINCIPAL DATA CONSIDERATIONS FOR MONITORING WELLS

Data Needed	Well Placement	Drilling	Material Selection	Slot Size
Site or material accessibility		X		
Rock type		X		
Soil characteristics:				
grain sized distribution				X
compaction	X	X		
strength (or structural) properties	X	X		
permeability	X			
porosity	X			
chemistry			X	
depth	X	X		
Hydrology:				
depth to water table	X			
hydraulic gradient (potentiometric surfaces)	X			
groundwater quality			X	
rate and direction of groundwater	X			
Waste description (waste and leachate)				
chemical characteristics	X		X	
physical characteristics	X		X	
Well characteristics	X	X	X	
Economics	X	X	X	

Source: ADL, 1976

TABLE 5-5
COST ESTIMATES FOR MONITORING WELLS

Monitoring Technique & Construction Method	Price Per Diameter of Installation Well (1982 dollars[a])		
	51mm (2-inch)	102mm (4-inch)	152mm (6-inch)
Screened over a single interval (plastic screen and casing)			
1. Entire aquifer	$2,770-6,400	$3,980-7,790	$11,070-12,980
2. Top 3 meters (10 feet) of aquifer	1,040-1,820	1,210-1,990	-
3. Top 1.5 meters (5 feet) of aquifer with drive point	170-350	-	-
Piezometers (plastic screen and casing)			
1. Entire aquifer screened			
a. Cement grout	3,630-8,130	4,840-9,520	11,940-14,710
b. Bentonite seal	3,200-7,180	4,070-8,560	11,500-13,750
2. Top 3 meters (10 feet) of aquifer screened			
a. Cement grout	1,990-3,550	2,080-3,720	-
b. Bentonite seal	1,560-2,600	1,640-2,770	-
Well clusters			
1. Jet-percussion			
a. Five-well cluster, each well with a 6-meter (20-foot) long plastic screen	4,300-6,570	-	-
b. Five-well cluster, each well with only a 1.5-meter (5-foot) long plastic screen	2,940-3,980	-	-
2. Augers			
a. Five-well cluster, each well with a 6-meter (20-foot) long staineless steel wire-wrapped screen	7,960-9,170	-	-
b. Five-well cluster, each well with only a 1.5-meter (5-foot) long gauze wrapped drive points	3,110-4,500	-	-

TABLE 5-5
COST ESTIMATES FOR MONITORING WELLS (Cont.)

Monitoring Technique & Construction Method	Price Per Diameter of Installation Well (1982 dollars[a])		
	51mm (2-inch)	102mm (4-inch)	152mm (6-inch)
3. Cable tool			
a. Five-well cluster, each well with a 6-meter (20-foot) long stainless steel wire-wrapped screen	-	-	$17,040-24,480
4. Hydraulic rotary			
a. Five-well cluster, each well with a 6-meter (20-foot) long plastic screen, casing grouted in place	-	$15,660-25,780	23,880-33,560
b. Five-well cluster, completed in a single large-diameter borehole 4.5-meter (15-foot) long plastic screens, 1.5-meter (5-foot) seal between screens	$7,340-10,170	14,270-19,030	-
Single well/multiple sampling point			
a. 33.5-meter (110-foot) deep well with 1-foot long screens separated by 1.2 meters (4 feet) of casing starting at 3 meters (10 feet) below ground surface	-	-	5,190-8,130
Sampling during drilling	-	5,190-8,130	5,700-9,000

[a] Cost estimates are for an aquifer composed of unconsolidated sand with a depth to water of 3 meters (10 feet) and a total saturated thickness of 30 meters (100 feet). Costs have been updated to 1981 dollars based on rates prevailing in the Northeast in Autumn, 1975. Actual costs will be lower and higher depending upon conditions in other areas. Therefore, the cost estimates will be most useful in determining the relative cost relationships among the monitoring techniques.

Source: Fenn et al, 1977

GLOSSARY[1]

CONTROL TECHNOLOGY TERMS

ABS pipe--Abbreviation for pipes made of acrylonitrile butadiene styrene, a type of plastic.

annular space--The space in a well between the well casing and sides of the borehole.

Aquifer Terms

confined--An aquifer is confined if the upper boundary of the aquifer is determined by (or confined by) a relatively impermeable stratum (called an aquitard). The potentiometric surface of a confined aquifer is generally higher than this boundary.

drawdown--The change in height of the water table (for unconfined aquifers) or potentiometric surface (for confined aquifers) radially around a well due to pumping.

homogeneous--An aquifer is homogeneous if the hydraulic conductivity is independent of position in the aquifer. At any two given points, therefore, hydraulic conductivity will be the same. Aquifers which do not have this characteristic are heterogeneous.

hydraulic conductivity--A measure of the rate at which fluid flows through a porous medium. It is a function of the characteristics of both the fluid and the medium. It is sometimes called the coefficient of permeability.

hydraulic gradient--The rate of change in hydraulic head between two points. It indicates the direction in which water will flow.

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[1] The Glossary is divided into two sections: Control Technology Terms (from Section 3) and Treatment Technology Terms (from Section 4). In addition, terms pertaining to aquifers and to soil are grouped together.

hydraulic head--The sum of the fluid pressure due to water depth (pressure head) and elevation above an arbitrary datum (elevation head). This determines how high water will rise in a well penetrating the aquifer to a given depth.

isotropic--An aquifer is isotropic if the hydraulic conductivity is independent of the direction of flow. At any given point, therefore, vertical hydraulic conductivity is equal to horizontal hydraulic conductivty. Aquifers which do not have this characteristic are anisotropic.

leaky--An aquifer is leaky if there is inflow or outflow through the underlying or confining layer (i.e., the underlying or confining layer is "leaky"). (Freeze and Cherry, 1979).

potentiometric surface--An imaginary surface defining the height to which water would rise in a series of wells penetrating an aquifer. It is a measure of the hydraulic head of the aquifer. It is also called a piezometric surface.

specific yield--Volume of water yielded per unit surface area per unit drop in the water table in an unconfined aquifer. In a confined aquifer, this is called the storativity and is defined in terms of a unit drop in the potentiometric surface.

transmissivity--An expression of the amount of water that can be extracted from an aquifer in a given amount of time. Typical FPS units are gals/day/ft and SI units are m^2/s. It is defined as the hydraulic conductivity times the saturated thickness of the aquifer (Freeze and Cherry, 1979).

unconfined--An aquifer is unconfined when the water table defines the upper boundary of the aquifer (Freeze and Cherry, 1979). The potentiometric surface of an unconfined aquifer is generally at the water table. Unconfined aquifers are also called water table or phreatic aquifers.

backfill--"The operation of refilling an excavation. Also the material placed in an excavation in the process of backfilling" (EPA, 1976, Vol. 1).

banquette--A local extension of the land side slope of a dike constructed to provide construction access or added stability where required (SCS, 1972).

bedrock--Relatively impermeable rock "lying in the position where it was formed and not underlain by any material other than rock" (Merritt, 1976).

bentonite--A clay made of decomposed volcanic ash which swells when wetted (Merritt, 1976).

diatomaceous earth--Deposits of well-graded silaceous phyto-plankton (diatoms) the size of very fine silt used primarily as a filter medium.

diversion--The combination of a dike and a channel constructed immediately upslope of the dike, used to intercept surface flow.

drainage area--That portion of the land surface which naturally drains across a given line of interest. It is an important factor in determining the quantities of water that can arrive at surface water control structures.

eutrophic--A condition in a body of water which promotes nuisance algae growths. It is usually caused by high nutrient concentrations.

fetch--Distance of open water, used in calculating wave height.

freeboard--The distance between design peak water levels and the top of a structure such as a levee or dike. It is especially important for earthen structures in providing a measure of safety to prevent overtopping.

gabion--A mesh container filled with rocks or stones used in the construction of dams, channels, and basin sidewalls (EPA, 1976, Vol. 1).

grade--The angle of a structure across the slope. A dike of 0% grade would, therefore, cause water to pond behind it while a positive grade would allow water to flow along the dike.

groundwater (or water) table--The upper limit of the part of the soil or underlying rock material that is wholly saturated with water. The locus of points in soil water at which the hydraulic pressure is equal to atmospheric pressure (EPA, 1976, Vol. 1).

gunite--A trademark for a concrete mixture sprayed under pressure over steel reinforcements.

neoprene--A synthetic rubber produced by the polymerization of chloroprene; it is highly resistant to oil, heat, light and oxidation.

nomograph--A diagram used with a straight edge to find dependent variables when independent variables are given. For example, given slope, discharge, and velocity of a parabolic channel, it is possible using a nomograph to find necessary top width and channel depth.

Number 200 sieve--Instrument which allows only soil with particle size smaller than fine sand (.074mm) to pass through.

Proctor density--Maximum density on a smooth curve of dry soil density versus soil moisture content determined by the standard Proctor density test. Also called the standard American Association of State Highway Officials (AASHO) density.

PVC--Abbreviation for polyvinylchloride; a type of plastic.

remedial action--Defined by CERCLA, section 101(24), as "those actions taken ... in the event of a release or threatened release of a hazardous substance into the environment, to prevent or minimize the release of hazardous substances so that they do not migrate to cause substantial danger to present or future public health or welfare or the environment." In the context of this report it also includes removal actions.

riprap--Broken rock, cobbles, boulders, or similar material placed on earth surfaces such as a levee or dike, for protection against soil erosion due to the action of water (EPA, 1976, Vol. 1).

runoff--Any water, leachate or liquid which flows over land from onsite to offsite, or that portion of precipitation which flows overland.

runon--Any water, leachate, or liquid which flows from offsite to onsite.

sec-marsh--A unit of viscosity. It is measured by means of a standard test using a marsh funnel. A liquid which takes 40 seconds for 964 cubic centimeters to drain from a marsh funnel is said to have a viscosity of 40 sec-marsh. Water has a viscosity of 28 sec-marsh.

slope--Rate of change in elevation of the land surface. A slope defined by a horizontal distance of two meters and a vertical rise of one meter can be expressed as a fraction (1/2 or .5), a percent (50%), or a ratio (2:1).

slope length--The distance along a slope between successive natural or man-made obstacles which impede the flow of surface water. It is an important factor in determining a slope's resistance to erosion.

slope steepness--The average slope of the land surface. It is an important factor in determining a slope's resistance to erosion.

Soil Terms

soil--"1. The unconsolidated mineral and organic material on the immediate surface of the earth that serves as a natural medium for the growth of land plants. 2. A kind of soil; that is, the collection of soils that are alike in specified combinations of characteristics. Kinds of soil are given names in the system of soil classification. The terms 'the soil' and 'soil' are collective." (EPA, 1976, Vol. 1).

grain size distribution--A plot of the percent, by weight, of soil material retained versus the logarithm of the sieve opening.

permeability--"The ability of a soil to conduct or discharge water under a hydraulic gradient." It is a function of particle size, soil density, and degree of saturation (Merritt, 1976).

plasticity--The ability of a soil "to deform rapidly without cracking, crumbling, or volume change and with relatively small rebound when the deforming force is removed." (Merritt, 1976).

porosity--Percent void space (filled with air or other fluid) in a soil.

strength properties--Properties of a soil which determine important characteristics such as ultimate bearing capacity, stability of embankments, and pressure against underground walls or barriers (Merritt, 1976). These properties include soil density, consistency, compressibility, and shearing strength.

texture--Measures the appearance of the soil in terms of particle size, shape, and gradation. It is important in determining other properties, such as maximum density, compressibility, and others (Merritt, 1976).

stabilize--To "settle, fix in place, make non-moving" (EPA, 1976, Vol. 1), often by means of vegetation or placement of surface materials such as straw. It usually refers to holding soil in place to prevent erosion or to allow seed to take root.

staging area--A section of a site with adequate controls (e.g., paved and drained, runon prohibited) for the safe storage and handling of drummed waste or other hazardous materials.

straw-bale check dam--A temporary barrier constructed of staked down straw bales used to intercept sediment or slow down channel flow to allow vegetation to take hold. It has a life expectancy of three months or less. (EPA, 1976, Vol. 2).

swale--"A ditch, hollow, or depression." (EPA, 1976, Vol. 1).

transpiration--Water loss from leaves and other plant organs to the atmosphere.

24-hour, 25-year rainfall--The intensity and quantity of water discharged by a storm with a 24-hour duration which has the probability of occuring once every 25 years. It has a 4% chance of occuring in any given year.

uncontrolled hazardous waste disposal sites--Refers to a site where hazardous wastes have been disposed or spilled in such a way as to pose a threat to human welfare or the environment. Also called abandoned or inactive hazardous waste sites.

TREATMENT TECHNOLOGY TERMS

aerobic--Refers to biological processes which require molecular oxygen.

alcohols--A class of organic compounds characterized by a hydroxyl group. Methanol, ethanol, and propanol are examples of alcohols.

aliphatics--a class of organic compounds characterized by a chain arrangement of carbon atoms (Hawley, 1981).

amines--A class of organic compounds characterized by ammonia with one or more hydrogens replaced by an alkyl group.

ammonia--A colorless gas composed of nitrogen and hydrogen atoms which is extremely soluble in water.

anaerobic--Refers to biological processes which require the absence of molecular oxygen.

aromatics--A class of organic compounds characterized by one or more cyclic rings which contain double bonds. Benzene is a prominent member of this class.

asphaltic bitumen--black or dark colored cement-like substance composed mainly of high molecular weight hydrocarbons (TRD 4).

BOD (Biological Oxygen Demand)--"A measure of the relative oxygen requirements of waste-waters, effluents and polluted waters. BOD values cannot be compared unless the results have been obtained under identical test conditions. The test is of limited value in measuring the actual oxygen demand of surface waters." (TRD 4).

COD (Chemical Oxygen Demand)--"A measure of the oxygen equivalent of that portion of the organic matter in a sample that is susceptible to oxidation by a strong chemical oxidant." (TRD 4).

colloidal particles--"Particles that are so small that the surface activity has an appreciable influence on the properties of the particle." (TRD 9).

cyanide--A class of compounds characterized by the presence of a cyanide group which consist of a carbon atom triply bonded to a nitrogen atom.

detention time--The time period that a waste stream is retained in contact with a treatment process, also referred to as retention time.

EDTA--Ethylenediamine tetraacetic acid.

effluent--"A waste product discharged from a process" (EPA, 1980).

elutriate--Liquid phase of a wash which is recovered by filtering or decanting.

ethers--A class of organic compounds characterized by an oxygen molecule singly bonded to two organic groups of atom; i.e., R-O-R where R represents an organic group.

flocculation--"The coalescence of a finely-divided precipitate" (EPA, 1980).

halocarbons--A class of organic compounds which contain carbon, one or more halogens, and sometimes hydrogen (Hawley, 1981).

influent--"A process stream entering the treatment system" (EPA, 1980).

immiscible--liquids which cannot be mixed or blended to form a uniform solution (e.g., oil and water).

insolation--Average solar flux reaching the earth's surface, in watts per square meter.

leachate--Any liquid, including any suspended components in the liquid, that has percolated through or drained from hazardous wastes (Fed. Reg. 45, 33075, May 19, 1980).

leachate plume--The volume which encompasses the spread of leachate from its source.

metals--Elements which form positive ions when their salts are dissolved in water (Hawley, 1981).

MLVSS (mixed liquor volatile suspended solids)--Concentration of volatile suspended solids in a waste water and microorganisms mixture of an activated sludge treatment process. Volatile suspended solids are the fraction of total suspended solids which are combustible at 550°C. Volatile suspended solids levels are a rough approximation of the organic portion of the total suspended solids (EPA, 1971).

nitrification--oxidation of nitrogen to nitrates; typically in biological waste treatment nitrogen present in ammonia is oxidized to form nitrate ions.

129 Priority Pollutants--List of toxic pollutants for which the EPA is required to publish effluent standards under Sec 307 of the Clean Water Act of 1977.

organics--Compounds containing carbon.

PCBs (Polychlorinated biphenyls)--A group of toxic chlorinated hydrocarbons most commonly used as heat transfer fluids. PCBs are persistent in the environment and are a suspected carcinogen.

pesticide--"A broad term that includes all chemical agents used to kill animal and vegetable life which interfere with agricultural productivity regardless of their mode of action." (TRD 4). DDT, chlordane, aldrin, and dieldrin are examples of pesticides.

phenols--A class of organic compounds characterized by one or more hydroxy groups bonded to a benzene ring (Hawley, 1981).

phthalates--A class of organic compounds characterized by adjacent ester groups attached to a benzene ring. Examples of phthalates are Di-N-Butylphthalate, Diethylphthalate, and Phthalimide.

polynuclear aromatics--A class or organic compound characterized by three or more aromatic rings.

post treatment--Processing of waste streams to remove secondary pollutants which have been subject to a treatment process designed to remove the object pollutants; e.g., denitrification of a waste water stream after biological treatment to lower BOD.

pretreatment--Processing of waste streams prior to a treatment process designed to remove the object pollutants; e.g., equalization and/or pH adjustment prior to biological treatment to reduce a wastewater BOD.

reagent--"Any substance used in a reaction for the purpose of detecting, measuring, examining, or analyzing other substances" (Hawley, 1981).

sludge--"any solid, semisolid, or liquid waste generated from a municipal, commercial, or industrial waste water treatment plant, water supply treatment plant, or air pollution control facility exclusive of the treated effluent from a wastewater treatment plant." (TRD 6).

TDS (total dissolved solids)--"Solids capable of passing through a standard glass fiber filter and dried to constant weight at 180°C" (EPA, 1971). Also referred to as filterable solids.

TKN (total Kjeldahl nitrogen)--The sum of free ammonia and organic nitrogen compounds which are converted to ammonia sulfate under conditions described in the reference EPA, 1971.

treatment--"Any method, technique, or process, including neutralization designed to change the physical, chemical, or biological character or composition of any hazardous waste so as to neutralize such waste, or so as to recover energy or material resources from the waste, or so as to render such waste non-hazardous or less hazardous; safer to transport, store, or dispose of; or amenable for recovery, amenable for storage, or reduced in volume." (TRD 6).

TSS (total suspended solids)--"Solids that either float on the surface of or are suspended in water, wastewater, or other liquids, and which are largely removable by laboratory filtering as described in "Standard Methods of the Examination of Water and Wastewater," and referred to as nonfilterable residue." (TRD 4).

zeolites--Hydrated silicates of aluminum and sodium and/or calcium which are used as ion exchange resins.

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